MetaNano 2016

05-09 September, Anapa, Russia

Book of Abstracts

ITMO UNIVERSITY

RSF | Russian Science Foundation

Program of the MetaNano Conference

Monday, 05/09				
07.30-10.00	**Registration**			
09.45-10.00	**Opening word by the Conference Chair Prof. Pavel Belov**			
	Room 1			
10.00-10.45	A. Lavrinenko	Mid Infrared hyperbolic metamaterials. *Page 1*		
10.45-11.15	I. Shelykh	Transport properties of electromagnetically dressed graphene. *Page 2*		
11.15-11.45	C. David, J. Christensen, N. A. Mortensen	Spatial dispersion in plasmonic crystals. *Page 3*		
11.45-12.15	**Coffee break**			
	Room 1		**Room 2**	
12.15-12.45	O.V. Kibis	Electromagnetic dressing as a tool to control nanostructures. *Page 4*	R. Malureanu, A. Lavrinenko	Plasmonic nanostructures fabrication technology. *Page 8*
12.45-13.00	V. Shahnazaryan, I. A. Shelykh, O. Kyriienko	Attractive Coulomb interaction of 2D Rydberg excitons. *Page 5*	P.N. Melentiev, A.E. Afanasiev, A.A. Kuzin, V.M. Gusev, O.N. Kompanets, V.I. Balykin	A nanoscale UV light source. *Page 9.*
13.00-13.15	M. Hasan, I. Iorsh, D. Gulevich, I. Shelykh	Topological edge states and quantum spin Hall phase in irradiated arrays of quantum rings. *Page 6*	I. Mukhin, F. Komissarenko, S. Lukashenko, A. Golubok	Pick-and-place Nanomanipulation and nanomechanics. *Page 10*
13.15-13.30	V.E. Babicheva, M.I. Petrov, K.V. Baryshnikova, P.A. Belov	Dielectric Huygens metasurfaces: the role of high-index substrate. Page 7		
13.30-15.15	**Lunch**			
	Room 1		**Room 2**	
15.15-15.45	I. Nefedov	Lateral Casimir effect near a smooth slab of asymmetric hyperbolic metamaterial. *Page 11*	N.A. Inogamov, V.V. Zhakhovsky, K.P. Migdal, D.K. Ilnitskiy	Submicron-micron size 3D features artificially created by tightly focused laser pulse for plasmonics applications. *Page 17*
15.45-16.15	M. Gorlach, A. Chebykin, S. Glybovski, P.A. Belov	Anisotropy of metamaterials induced by spatial dispersion. *Page 12*	O. Pena-Rodriguez	Controlling the assembly and welding of gold nanorods by means of femtosecond laser pulses. *Page 18*
16.15-16.30	M. Cojocari, A.A. Basharin	Diamagnetism due to toroidal response. *Page 13*	A. Krasilin, K. Volodina, V. Milichko, S. Makarov, D. Zuev, D. Baranov, A. Vinogradov, A. Krasnok, P. Belov	Protein temperature and conformation control at the nanoscale. *Page 19*
16.30-16.45	K. Ladutenko	Beyond superabsorption. how to design efficient absorption of light by nanoparticles. *Page 14*	A. Bolshakov, G. Sapunov, A. Mozharov, I. Shtrom, G. Cirlin, I. Mukhin	Synthesis and study of GaN nanowires and nanotubes on Si. *Page 20*
16.45-17.00	R. Savelyev, A. Yulin, A. Krasnok, Yu. Kivshar	Solitary waves in chains of silicon nanoparticles. *Page 15*	V. Milichko, S. Makarov, A. Yulin, A. Vinogradov, A. Krasilin, V. Dzyuba, E. HeyHawkins, P. Belov	Manipulation of excitons in metal-organic van der Waals crystals at room temperature. *Page 21*
17.00-17.15	A. Shalin, A. Bogdanov, P. Belov	Optical forces in metamaterials. *Page 16*	I. Vrubel, V. Milichko, R. Polozkov	Quantum-mechanical modeling of spatial and electronic structure of Zn-based metal-organic framework. *Page 22*
Tuesday, 06/09				

	Room 1	
10.30-11.15	A. Rubtsov	Superconductor metamaterials: brand-new correlated systems.
11.15-11.45	S. G. Tikhodeev, S. V. Lobanov, N. A. Gippius, T. Weiss, C. Schneider, J.Gessler, M. Kamp, S. Hoefling, A. A. Maksimov, E. V. Filatov, I. I. Tartakovskii, and V.D. Kulakovskii	Controlling circular polarization of light emitted by quantum dots using chiral photonic crystal slabs. *Page 23*
11.45-12.15	**Coffee break**	

	Room 1		Room 2	
12.15-12.30	S. Gavrilov	Spin chaos in cavity-polariton condensates. *Page 24*	C. Simovski, M.-S. Mirmoosa	Thermophotovoltaic systems enhanced by nanowires. *Page 28*
12.30-12.45				
12.45-13.00	A. Pervishko, O.V. Kibis, I.A. Shelykh	Polarization Diffusion in Polariton Microcavities with an External Magnetic Field	S. Kosulnikov	Manipulating the electromagnetic fields using wire media. *Page 29*
13.00-13.15	A. Sheremet, Yu. Rubo, A.V. Kavokin	Stochastic conversion processes in bosonic condensate of exciton-polaritons. *Page 25*		
13.15-13.30	D. Gulevich, D. Yudin, I. Iorsh, D. Skryabin, I. Shelykh	Nonlinear topological excitations in polaritonic kagome lattice. *Page 27*	M. Omelyanovich, Y. Ra'di, C. Simovski	Full broadband absorption of perovskite solar cells with plasmonic nanoparticles. *Page 30*
13.30-13.45			C. David	Mutli-type particle layer enhanced absorption for PV applications. *Page 31*
13.30-13.45			P. Voroshilov, C.R. Simovski	Optical domino-modes in arrays of metal nanostrips and their application in photovoltaics. *Page 32*
13.45-15.00	**Lunch**			

	Room 1		Room 2	
15.00-15.30	S. Maslovski	Light trapping in metamaterial thermal black holes and wormholes. *Page 33*	A. Uskov, I. E. Protsenko, I. V. Smetanin R. Sh. Ikhsanov, V. E. Babicheva, S. V. Zhukovsky, A.V. Lavrinenko, H. Xu, E. P. O'Reilly	Photoemission of electrons from plasmonic nanoantennas. *Page 40*
15.30-15.45	A. Yulin, I. Chestnov, O. Yegorov	Stationary and dynamical states of polaritons in discrete systems. *Page 34*	N. Nefedkin, E.S. Andrianov, A. Pukhov, A.P. Vinogradov, A. A. Lisyansky	Transition from collective spontaneous emission to coherent superradiance of atoms placed near plasmonic structure. *Page 41*
15.45-16.00	I. Chestnov	Nonlinear dynamics and the band-structure of the exciton-polariton condensate in one-dimensional periodic lattices. *Page 35*	P.N. Melentiev, A.E. Afanasiev, A.A. Kuzin, V.I.Balykin	Violation of nonreciprocity principle in a planar optical system. *Page 42*
16.00-16.15	A. Alodjants	Permanent Rabi oscillations with Exciton-Polariton Non-equilibrium Condensates. Page *37*	V. Shishkov	Hermitian description of localised plasmons in dispersive dissipative subwavelength nanostructures. *Page 43*
16.15-16.30	A. Khramova, N.Khokhlov, V.I. Belotelov	Magneto-optical light modulator with the domain wall manipulation via flexomagnetoelectric effect. *Page 39*	N. Nefedkin	Noise suppression in nanoplasmonic systems. *Page 45*

Wednesday, 07/09

12:00	**All-day excursion to Abrau Durso wineries**

Thursday, 08/09

	Room 1	
10.00-10.45	M. Silverinha	Topological photonics in an electromagnetic continuum. *Page 67*
10.45-11.15	A. Khanikaev	Topological metamaterials for light and sound. *Page 68*
11.15-11.45	A.K. Samusev, O. Takayma, R. Malureanu, I. Mukhin, D. Permyakov, D. Baranov, I. Iorsh, A. Bogdanov, A. Lavrinenko	Attenuated total reflection spectroscopy of hybrid optical surface waves in anisotropic metasurface. *Page 69*
11.45-12.15	**Coffee break**	
11.45-13.30	**Poster session**	
	Y.Y. Arlou, S.V. Maly	Hybridization of MAB and L-MAB methods. *Page 46*
	S.V. Maly, H.S. Arlova	The electromagnetic properties of composite materials based on the volume arrays of conducting fibers with dielectric insertions. *Page 47*
	A. Trofimov, E. Kolobkova, N. Nikonorov.	The investigation of fluorophosphate glass doped with ZnS optical properties after ion exchange. *Page 48*

	S.A. Moskalenko, I.V. Poldesny, E.V. Dumanov	Two-dimensional cavity magnetoexciton-polaritons. *Page 49*
	D.S. Chub	Ab initio calculation of the complex dielectric function of cobalt octaethylporphyrin by the projector-augmented-wave method and GW approximation. *Page 50*
	M. Yu. Barabanenkov	Fabrication of diffraction gratings and 2D photonic crystals in a Si on insulator waveguide by plasma and wet etching of Si. *Page 51*
	S. Moiseev	Thin film generator of surface plasmon polariton pulses. *Page 52*
	K.G. Belyaev, T.V. Shubina, M.A. Semina, A.V. Rodina, A.A. Toropov, S.V. Ivanov	Resonant energy transfer in epitaxial CdSe quantum dots. *Page 53*
	O.N. Kozina, L.A. Melnikov, A.S. Zotkina, I.S. Nefedov	Amplification of the THz oscillations and lasing effect in asymmetrical graphene-semiconductor hyperbolic metamaterial. *Page 54*
	S.V. Krasikov, I. Iorsh	Self-consistent Purcell factor and spontaneous topological transition in hyperbolic metamaterials. *Page 55*
	D. O. Ignatyeva	Garnet-based magnetoplasmonic sensor with ultra-high SPR quality factor. *Page 56*
	D. Pavlov, L. Butko, A. Anzulevich	Refraction angle of electromagnetic wave on a wired structure prism. *Page 57*
	I.V. Bychkov, D.A. Kuzmin, V.G. Shavrov, V.V. Temnov	Magneto-plasmonic effects in graphene-covered gyrotropic nanowires. *Page 58*
	D.A. Kuzmin, I.V. Bychkov, V.G. Shavrov	Fundamental transverse plasmonic mode of graphene cylinders. *Page 59.*
	A. Anzulevich, L. Butko	Radia and Conductivity dependencies of permeability of mettalized particles. *Page 60*
	S.A. Kolodny, D.A. Zuev, A.E. Krasnok, P.A. Belov	Inuence of fs-laser melting on the optical properties of hybrid dimer nanoantennas. *Page 61*
	K.V. Baryshnikova, P.B. Ginzburg, A.S. Kadochkin, A.S. Shalin, C.R. Simovsky	Separation of electric and magnetic field in silicon structure at nanoscale. *Page 62*
	Kolodeznyi E.S., Kurochkin A.S., Egorov A.Yu., Gadzhiev I.M., Buyalo M.S., Bougrov V.E.	High optical gain in phosphorus free 1550 nm laser diodes *Page 63*
	G.P. Zograf, S.V. Makaro, D.A. Zuev, V.A. Milichko, I.A. Mukhin, A.E. Krasnok, P.A. Belov	Femtosecond laser ablation for fabrication of gold-silicon core-shell nanoparticles. *Page 64*
	A.V. Sinelnik, K.B Samusev	fabrication and optical studies of two-dimensional photonic structures. *Page 65*
	S.V. Li, A.E. Krasnok, P.A. Belov	Chiral near- eld formation with all-dielectric nanoantennas. *Page 66*
13.30-15.00	**Lunch**	

	Room 1		**Room 2**	
15.00-15.15	P. Kapitanova, S. Kershis, A. Fazdalov, P. Belov	Electromagnetic field visualizer based on wire metamaterial. *Page 70*	D. Zuev, S. Makarov, V. Milichko, A. Krasnok, P. Belov, D. Baranov, A. Miroshnichenko, I. Mukhin, I. Morozov	Optical properties tuning of hybrid nanoantennas. *Page 74*
15.15-15.30	S. Glybovski, J. Baena, J. del Risco, A. Slobozhanyuk, P. Belov	Self-Complimentary Metasurfaces: from Basic Equations to Practical Designs of Polarization Converters. *Page 71*	S. Makarov, T. Voitova, A. Tsypkin, V. Milichko, I. Mukhin, A. Yulin, E.Putilin, M. Baranov, A. Krasnok, P. Belov	Self-Adjusted All-Dielectric Metasurface for Enhanced Third Harmonic Generation. *Page 75*
15.30-15.45	A. Sayanskiy, S. Glybovski, I. Meshkovskiy, V. Akimov, P. Belov	The wideband spherical Luneburg lens based on an arti cial-dielectric microwave metamaterial. *Page 72*	D. Permyakov, R. Bakker, Y. Yu, D. Markovich, R. Paniagua-Dom´ınguez, L. Gonzaga, A. Samusev, Yu.Kivshar, B. Luk'yanchuk, A.I. Kuznetsov	Enhancement of magnetic and electric fields with silicon nanodimers. *Page 76*
15.45-16.00	M. Odit, P. Kapitanova, A. Andryieuski, A. Lavrinenko, P. Belov	Experimental demonstration of microwave metasurface. *Page 73*	P. Dmitriev, D. Baranov, V. Milichko, S. Makarov, I. Mukhin, A. Samusev, A. Krasnok, P. Belov, Y. Kivshar	Raman Scattering from Crystalline Silicon Nanoparticles Enhanced by Mie Resonances. *Page 77*
16.00-16.15	M. Song, P. Kapitanova, I. Iorsh, P. Belov	Near field wireless power transfer using magnetic modes in high-index dielectric resonators.	I. Sinev, I. Iorsh, A. Bogdanov, D. Permyakov, F. Komissarenko, I. Mukhin, A. Samusev, A. Miroshnichenko, Yu. Kivshar	From high-Q magnetic dipole scattering to broadband electric eld localization by silicon nanoparticle on metal. *Page 78*
16.15-16.30			E. Romanova, N. Fedyukina, S. Guizard, T. Benson, A. Seddon	Photo-induced phenomena on the surface of glassy semiconductors studied with the femtosecond resolution in time. *Page 79*

16.30-17.00	**Coffee Break**	
17.00-17.30	V. Volkov	Plasmonic nanoguides: fundamentals and applications. *Page 80*
17.30-18.00	A.Karabchevsky, A. Katiyi	Nano-tapers: squeezing light in a dielectric nano-guide for overtone spectroscopy. *Page 81*
18.00-18.30	M.V. Rybin, M.F. Limonov	Inverse dispersion method for calculation of photonic band diagrams: application to the transition from photonic crystals to all-dielectric metamaterials. *Page 82*
18.30-19.00	M. Makhonin	Chirality in nanophotonic waveguides with embedded quantum dots. *Page 83*

Friday, 09/09

	Room 1	
10.00-10.45	P. Cilibrizzi, P. Lagoudakis	Spinor polariton condensates galore: from spin whirls to half-skyrmions
10.45-11.15	D. Filonov, V. Kozlov, Y. Yankelevich and P. Ginzburg	Time-Varying Metamaterials. *Page 84*
11.15-11.45	C. Rockstuhl, I. Fernandez-Corbaton, S. Nanz	New insights into an old topic: The Multipole Expansion. *Page 85*
11.45-12.15	**Coffee Break**	

	Room 1		**Room 2**	
12.15-12.30	M. Yu. Barabanenkov, Yu.N. Barabanenkov	Mutual excitation of two nested 2D periodic chains and excitation transfer along linear chain of plasmonic particles. *Page 86*	O.V. Borovkova, A.N. Kalish, G.A. Knyazev, P.O. Kapralov, V.I. Belotelov	Enhanced Magneto-Optical Effects in Active Plasmonic Nanostructures. *Page 90*
12.30-12.45	D.A. Sylgacheva, N.E. Khokhlov, A.N. Kalish, V.I. Belotelov.	Waveguide modes in one-dimensional magneto-photonic crystals. *Page 87*	O. Polischuk, V.V. Popov	Amplification of cross-polarization conversion of terahertz radiation by an active graphene metasurface. *Page 91*
12.45-13.00	O. Yermakov, A.A. Bogdanov, I. Iorsh	Full control of the spin angular momentum of light in the plane of anisotropic metasurface. *Page 88*		
13.00-13.15	Z. F. Sadrieva, I. S. Sinev, K. L. Koshelev, A. K. Samusev, I. V. Iorsh, A. A. Bogdanov, O. Takayama, R. Malureanu, and A.V. Lavrinenko	Bound states in the continuum in one-dimensional photonic structures. *Page 89*	M. Morozov, V. Popov	Giant plasmon amplification in active graphene - hexagonal boron nitride heterostructures. *Page 92*
13.15-13.30	M. Scherbakov	Nonlinear optics of semiconductor metasurfaces.	A.A. Zyablovsky, E.S. Andrianov, I.A. Nechepurenko, A.A. Pukhov, A.P. Vinogradov, A.A. Lisyansky	Suitable equations for the description of transient regimes of the lasing in the surface plasmon lasers. *Page 93*
13.30-13.45				

13.45-15.15	**Lunch**	
	Room 1	
15.15-15.45	F. Ding, A. Pors, Y. Chen, Z. Wang, V. Shalaev, A. Kildishev, S. Bozhevolnyi	Light scattering control with reflective metasurfaces: from polarization control to random-phase scattering. *Page 94*
15.45-16.15	N. Dubrovina, E. Bochkova, S.N. Burokur, A. de Lustrac, A. Ramdane, A. Lupu	Symmetry approach to the dark modes metasurfaces. *Page 95*
16.15-16.30	A. Slobozhanuk, A. Schelokova, S. Glybovsky, I. Melchakova, P.A. Belov	Microwave metemeterials for MRI applications. *Page 96*
16.30-16.45	**Closing session**	
17:00	**Departure to Utrish. Conference Dinner**	

Mid-Infrared Hyperbolic Metamaterials

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Over the last decade, the concept of metamaterials has transferred the role of elementary constituents of matter (atoms) to small objects designed for certain physical properties [1]. These artificial building blocks are often referred to as meta-atoms. The freedom to design meta-atoms is nearly total, and thus it has been possible to obtain physical properties that cannot be exhibited by natural materials [2]. One of the latest trend in metamaterials are hyperbolic metamaterials (HMMs), which feature an extreme artificial anisotropy sufficient that the medium behaves as a metal in some directions and as a dielectric in others. It means that in such media, the effective permittivity tensor, which characterizes the properties exposed by the metamaterial, has components of different signs, e.g., $\varepsilon_x, \varepsilon_y < 0$ and $\varepsilon_z > 0$ or vice versa. As a result, the dispersion relation determining the wave vectors of propagating waves changes topology from a bounded ellipsoid to an unbounded hyperboloid [3]. Thus, plasmonic waves with large wave vectors - volume plasmon polaritons [4], which are evanescent in natural media, become propagating in HMMs. Thanks to these volume plasmon-polaritons, HMMs exhibit many pronounced physical effects such as enhancement of the photonic density of states, super-Planckian black-body radiation, far-field optical imaging of subwavelength objects, and superabsorption [3]. There is a growing demand for expansion of nomenclature of materials, which possess $\mathrm{Re}(\varepsilon) < 9$. The flexibility in choice of plasmonic materials [5] serves for the fast growth of mid-infrared (IR) plasmonics [6]. Similar to the cases of visible and near-IR regions, mid-IR plasmonics can contribute to many applications including e.g. thermal imaging, due to the peak emission wavelength for the temperatures ranging from 200-1400 K and the atmospheric transmission window both lying in the mid-IR [6].

One of perspective mid-IR plasmonic materials, which we adopt in our research, is Al-doped ZnO (AZO) [5]. We will report first on advanced fabrication routines involving atomic layer deposition to produce multilayers systems, which can effectively exhibit HMMs properties in mid-IR. Characterization of such structures confirmed the claim for effective hyperbolic properties of multilayers in the ranges with $\lambda > \mu$m. Remarkably, we are able to construct not only traditional horizontal multilayered metamaterials, but also HMMs with vertical AZO-air strata [7]. In the latter case a unique configuration is formed, when in addition to bulk plasmon-polaritons special surface waves Dyakonov plasmons [8] can propagate on top of the multilayer. The complete picture of their extraordinary properties, both simulated and observed in direct experiments will be provided.

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Magnetoelectronic properties of graphene dressed by a high-frequency field

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We solved the Schrdinger problem for electrons in two dimentional electronic systems (electron gas and graphene) subjected to both a stationary magnetic field and a strong high-frequency electromagnetic wave (dressing field). The found solutions of the problem are used to describe the magnetoelectronic properties of the systems. It follows from the analysis that both optical characteristics and electronic transport are very sensitive to the dressing field. Particularly, the field strongly changes the spectra of optical absorption and the Shubnikov-de Haas oscillations. As a result, the developed theory opens a way for controlling magnetoelectronic properties of two dimensional systems with light.

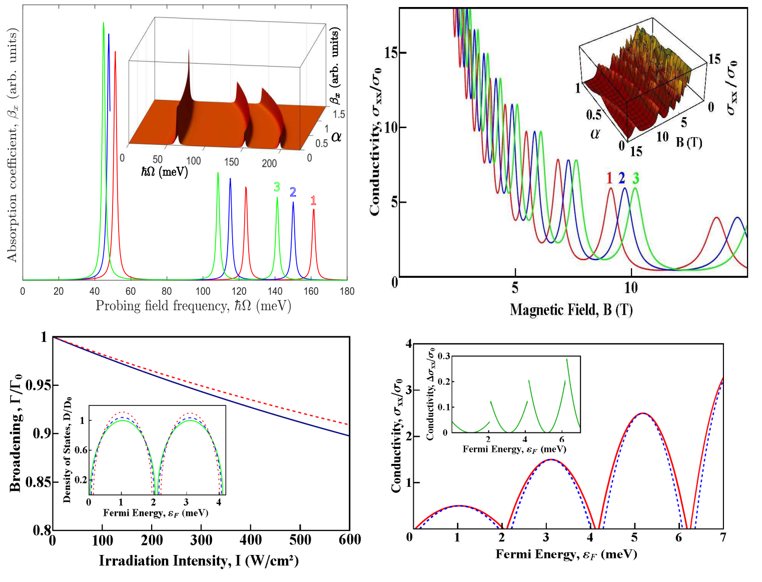

Fig. 1: (top left)The absorption coefficient of intrinsic graphene, β_x, at the temperature $T = 0$ as a function of the probing field frequency, Ω, for the decay rate $\Gamma = 1$ meV. The photon energy of dressing field is $\hbar\omega = 3$ meV and the different curves correspond to the different field intensities: (1) $I_0 = 0$; (2) $I_0 = 3.51$ W/cm^2; (3) $I_0 = 6.24$ W/cm^2.; (top right)The conductivity of a graphene layer, σ_{xx}, at the temperature $T = 0$ as a function of the magnetic field, B, for the Landau level broadening $\Gamma = 1$ meV and the Fermi energy $\varepsilon_F = 10$ meV. The photon energy of dressing field is $\hbar\omega = 3$ meV and the different curves correspond to the different field intensities: (1) $I_0 = 0$; (2) $I_0 = 1.56$ W/cm^2; (3) $I_0 = 2.63$ W/cm^2.; (bottom left) The dependence of the broadening of Landau levels, Γ, on the irradiation intensity, I, for the lowest two Landau levels with the numbers $N = 0$ (solid line) and $N = 1$ (dashed line) in GaAs-based 2DEG at the magnetic field $B = 1.2$ T; (bottom right) The dependence of the longitudinal conductivity, σ_{xx}, on the Fermi energy, ε_F, in GaAs-based 2DEG at the magnetic field $B = 1.2$ T, irradiation frequency $\omega = 2$ THz, and the natural broadening $\Gamma_0 = 1$ meV.

Spatial dispersion in plasmonic crystals

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In classical electrodynamics even short-ranged electron-electron interactions are suppressed. Dealing with nanosized metal structures makes it necessary to account for the quantum nature of electrons and include effects induced by the free conduction band. The successful observation of such quantum effects has fueled the interest in an accurate description of nonlocal electrons in a variety of metal nanostructures and particles. The impact of such nonlocal electron dynamics can efficiently be taken into account with semi-classical methods. [1, 2]

We address quantum interaction effects of the free electron gas in metal components in periodic plasmonic crystals to enhance the understanding of spatial dispersion in promising building blocks for photonic circuits. Additional pressure waves induced by the electron oscillation lead to a substantial change in the bandstructure and electromagnetic fields supported by a plasmonic crystal. A nonlocal methodology for nonlocal 2D plasmonic crystals, based on the extension of established periodic crystal concepts [3, 4], can give a full account on the impact of nonlocal response for important concepts and applications in photonics. We observe significant changes with respect to the local response approximation, see Fig. 1.

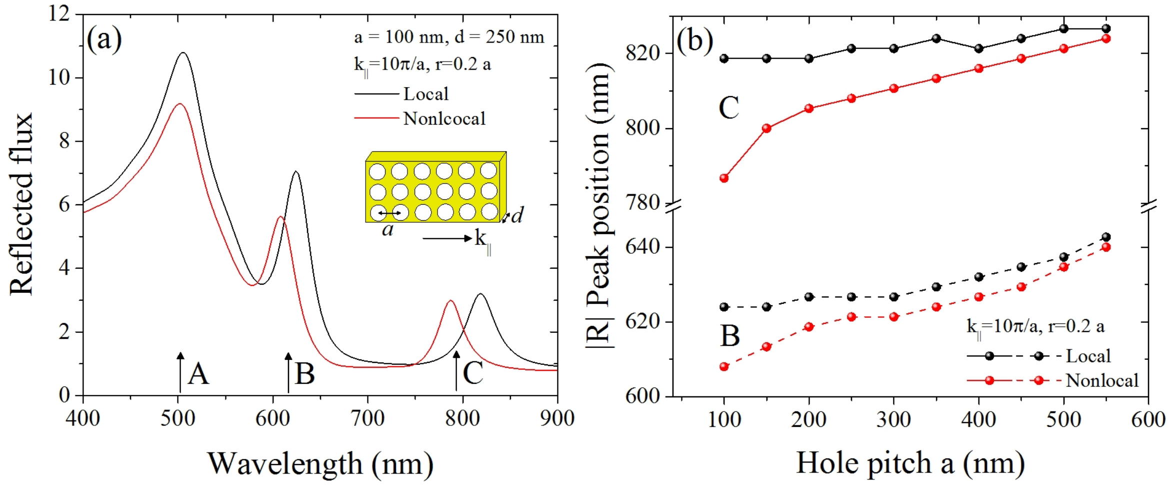

Fig. 1: Comparing the (a) reflected flux and (b) shift in peak positions as a function of hole separation for local and nonlocal plasmonic crystals using $k_{\parallel} = 10\pi/a, r = 0.2a, d = 250$nm and in (a) $a = 100$nm. The reflected light at A does not observe a significant shift, while B and C are strongly impacted in the nonlocal theory at this high parallel momentum.

References

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Electromagnetic dressing as a tool to control nanostructures

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Advances in laser physics achieved in recent decades have made possible the using of lasers as tools to manipulate electronic properties of various quantum systems. Since the strong interaction between electrons and an intense laser field cannot be described as a weak perturbation, it is necessary to consider the system "electron + field" as a whole. Such a composite electron-photon object, which was called "electron dressed by field" (dressed electron), became commonly used model in modern physics [1, 2]. The field-induced modification of energy spectrum of dressed electrons — also known as a dynamic (ac) Stark effect — was discovered experimentally in atoms many years ago and has been studied theoretically in various electronic systems. Particularly, it follows from recent studies that the electromagnetic dressing leads to unusual electronic effects in nanostructures.

In nanostructures with broken both time-reversal and inversion symmetry, the electromagnetic dressing results in composite electron-photon states which cannot be scattered elastically. As a consequence, the dressed electron gas in such nanostructures can flow without dissipation [4]. This quantum macroscopic phenomenon leads to the unconventional superconductivity which can take place, particularly, in asymmetrical quantum wells exposed to an in-plane magnetic field [5].

In the Dirac materials with linear electron dispersion, the strong interaction between massless Dirac fermions and circularly polarized photons leads to the composite electron-photon states with the gapped energy spectrum. Therefore, the electron-photon interaction results in metal-insulator transition. The stationary energy gap, induced by photons, and concomitant effects can be observed, particularly, in graphene exposed to a laser-generated circularly polarized electromagnetic wave [5].

Thus, the electromagnetic dressing can be considered as an effective tool to control electronic properties of various nanostructures. The work was supported partially by the Russian Ministry of Education and Science and the RFBR grant 14-02-00033.

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Attractive Coulomb interaction of 2D Rydberg excitons

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The Coulomb scattering processes of highly excited excitons in the direct bandgap semiconductor quantum wells are theoretically analyzed. The calculation of interaction potential for 2D excitons in the ground state can be done within the Coulomb scattering formalism [1]. We employ the straightforward extension of the mentioned theory to describe the interaction of excitons in the excited states. It is found that contrary to the interaction of ground state excitons the electron and hole exchange interaction between excited excitons has an attractive character both for s- and p-type 2D excitons. Further, it is shown that similarly to the three-dimensional highly excited excitons [2], the direct interaction of 2D Rydberg excitons exhibits van der Waals type long-range interaction. The results predict the linear growth of the absolute value of exchange interaction strength with an exciton principal quantum number, given by increase of effective interaction area due to the spread of wave functions. The mentioned evidence point the way towards enhancement of optical nonlinearity in 2D excitonic systems and studies of repulsive-attractive bosonic mixtures. The further details of the conducted research can be found in Ref. [3].

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Quantum Spin Hall phase and topologically protected edge states in the polariton rings lattices

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We study the dispersion and topological properties of the two-dimensional arrays of the coupled polaritonic rings in the presence of the external magnetic field. We show that these structures can be characterized by the nontrivial Chern numbers $\mathcal{C}_n = \pm 1, \pm 2$ and demonstrate the emergence of the topologically protected chiral edge states at the interfaces of these structures.

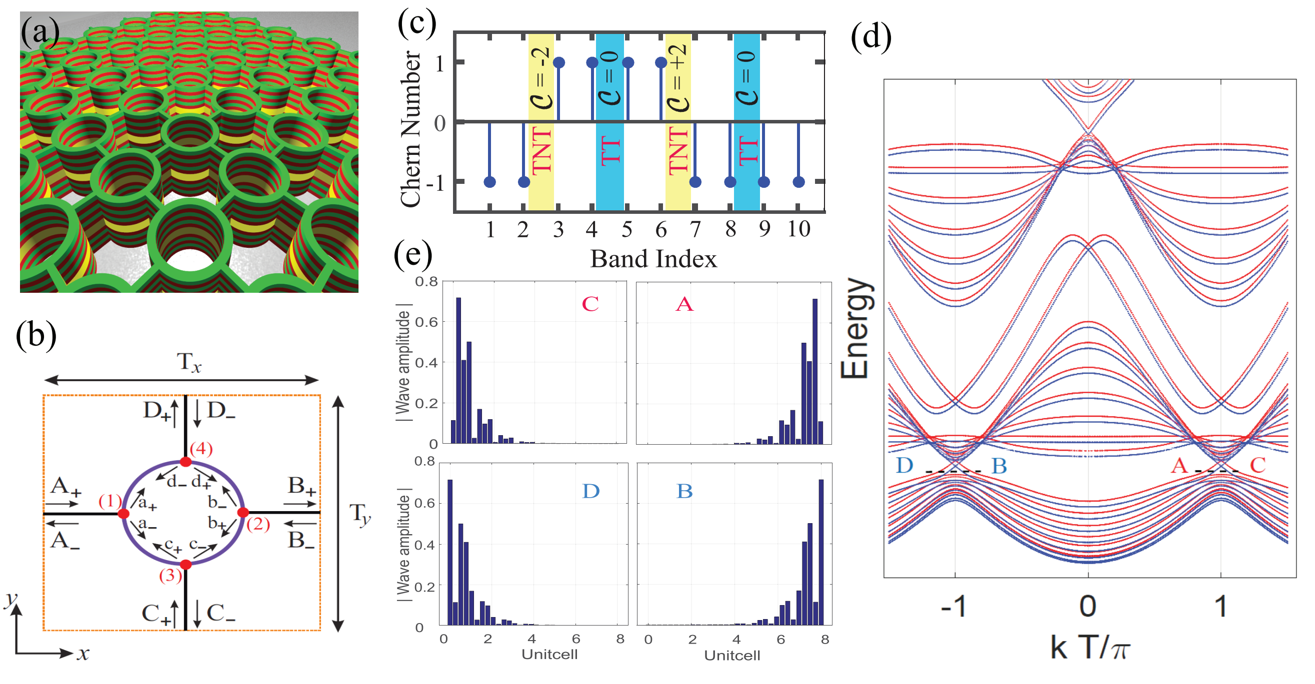

Figure 1: (a) Geometry of the structure: two-dimensional square lattice of the exciton-polariton ring resonators; (b) Unit cell of the structure: polariton rings are connected via leads at quantum point contacts (QPCs) which are shown as red filled-dots. (c) the Chern numbers of each band. The Chern invariants at bulk gaps are $\mathcal{C} = \pm 2$ for topologically non-trivial (TNT) gaps and $\mathcal{C} = 0$ for topologically trivial (TT) gaps. (d) Band structure of the stripe consisting of the 8 periods in y directions. (e) Field profiles of the edge states marked at the band diagram

Dielectric Huygens metasurfaces: the role of high-index substrate

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In this work, we study optical properties of all-dielectric metasurfaces on top of the high-index substrate. We propose a semi-analytical model separating contributions from the nanoparticle array and the bare substrate and compare it to whole-structure numerical simulations, which gives good agreement (Fig. 1). It allows demonstrating that reflection suppression occurs because of the destructive interference between waves scattered by electric and magnetic dipole moments and the wave reflected from the substrate itself [1]. Even though backscattering from the nanoparticle array (that is reflection) is high, one can obtain near-zero total reflection from the structure by destructive matching the metasurface-reflected wave with the substrate-reflected wave [2]. We also show good agreement between numerical and semi-analytical models for both sphere and disk nanoparticle arrays, although in case of disks, the coupling of resonant mode to the substrate is strong and requires an additional low-index layer.

We designed the structure with disordered array of nanospheres and numerically demonstrated a broadband reflection suppression: the reflectance is less than 10% at 300-650 nm wavelength range. The main mechanism, namely the possibility of destructive interference between substrate-reflected and multipole-scattered waves, can be used to reduce reflection at both narrow and broad spectral bands. Size and average density of nanoparticles are parameters that influence the most, while exact place of nanoparticles affects less.

The work has been supported by the Russian Ministry of Science and Education project #RFMEFI58416X0018

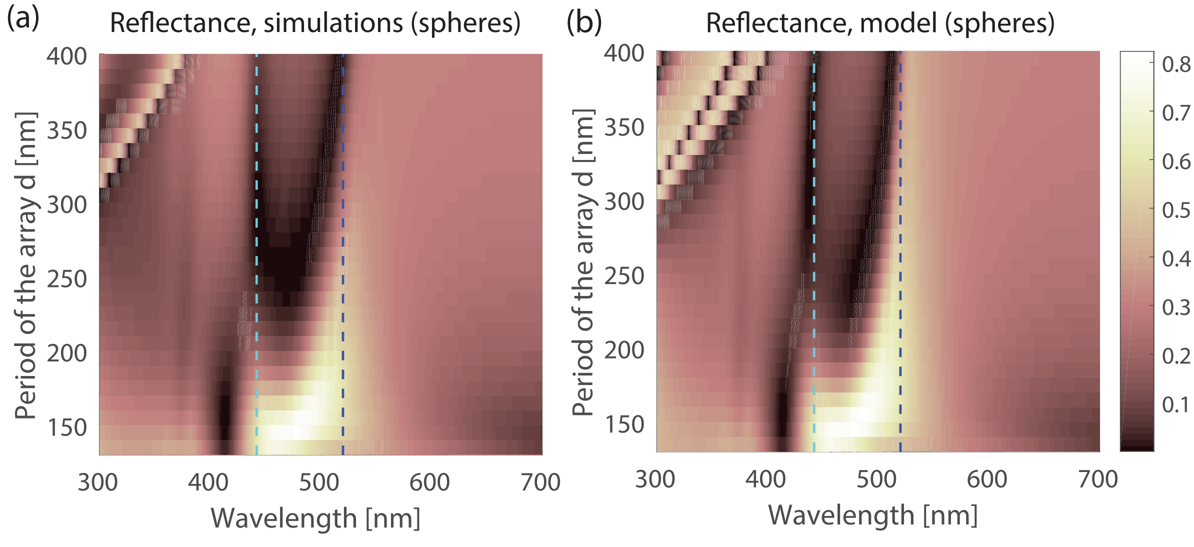

Fig. 1: Reflectance spectra of metasurfaces on Si substrate: (a) numerical simulations and (b) calculations according to the semi-analytical model (nanosphere array of $R = 60$ nm and different array periods $d = 130 - 400$ nm). Being defined as a maximum of scattering cross-section, MDR and EDR of single nanosphere with $R = 60$ nm are shown by the dashed lines: blue and light blue respectively.

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Plasmonic nanostructures fabrication technology

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The research field of nanophotonics, in particular plasmonics and metamaterials have witnessed recently a massive growth in interest and the devices nomenclature is expanding. Still, most of the devices proposed remain at a theoretical level due to the need for advancements in the fabrication technologies.

In this paper we will present an overview of the current fabrication technologies in the plasmonic nanostructures field. We will shortly present the possibilities for the dielectric structures manufacturing, but will mainly concentrate on the advancements in the metal deposition and patterning. Due to the ever more demanding fabrication precision, this nanofabrication field developed greatly in the last years. Thus, Au metal films, down to 6nm thin [1] can be deposited with very low roughness and without using metallic adhesion layers that decrease their performance. Also, multilayer structures of metals (Au) and dielectric (SiO_2) with 10nm period were obtained [2]. Although Au is the main metal used for plasmonics, and due to these advancements, the layer quality was greatly improved; other metals are starting to emerge as possible solutions for the visible and near-IR range [3]. This is also due to the fact that, once deposited, Au is extremely difficult to pattern. One reliable way to pattern Au is through using focused Ion beam: a technique not only slow and costly but that leads to various side-effects that will be discussed during the presentation. The other possibility for patterning Au is by depositing it on a pre-patterned substrate. Although it is a technique more used and less defect-prone, it brings its own limitations.

From the 3D fabrication point of view, the progress was more limited. Silver layers with thicknesses down to 30nm can be nowadays deposited on 3D structures [4, 5], but their use in devices is limited due to the big restrictions in processing of such structures.

An overview of the different techniques, their results and limitations will be presented, concentrating mainly on the deposition of thin metallic layers in a 2D geometry.

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A nanoscale UV light source

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Due to strong light absorption by metals, it is believed that plasmonic nanostructures cannot be used for generating intensive radiation harmonics in the UV spectral range. This work presents our results of investigation of nonlinear optical interaction with different types of individual plasmonic nanostructures to realize maximum conversion efficiency of third harmonics generation in the UV spectral range [1]. The strongest intensity of the THG emission was realized with a single gold nanostructure in a geometry of the Split-Hole Resonator (SHR) under the state-of-the-art experimentally realized conditions. To realize interaction with all spectral components of a 6 fs laser pulse several multipole plasmon resonances were simultaneously excited in the SHR nanostructure [2]. We report a strong nonlinear optical interaction at the frequencies of these resonances that leads to (i) the second harmonic generation, (ii) the third harmonic generation (THG), and (iii) the light generation at mixed frequencies. The THG near field amplitude reaches 0.6% of the fundamental frequency field amplitude, which enables the creation of UV radiation sources with a record high intensity. The UV THG may find many important applications including biomedical ones (such as cancer therapy).

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Pick-and-place Nanomanipulation and nanomechanics

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Micro- and nanomanipulation, based on the transportation of micro- and nanoobjects for the purpose of their investigation, or fabrication of complex structures, is very promising technique. Here we present a method of pick-and-place manipulation of single nanoparticle under influence of beam of a scanning electron microscope with using sharp metal tip based on 3D manipulator. Proposed method allows controllable pickup, move and placement of nanoparticles as well as visualization of the process and the result of manipulation in real time on electron images.

Lateral Casimir effect near a smooth slab of asymmetric hyperbolic metamaterial

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Fluctuating electromagnetic fields are responsible for such important phenomena as thermal emission, radiative heat transfer, the van der Waals interaction, the Casimir effect, and the van der Waals friction between bodies [1]. The conventional Casimir force is orthogonal to plane interfaces bounding a vacuum gap and it can be either attractive, if the separating distance between bodies is small and interaction is due to nonhomogeneous field of evanescent waves, excited by fluctuating currents, or repulsive, if the normal component of the Poynting vector dominates over the evanescent waves contribution. The lateral component of the Poynting vector, integrated over whole spatial spectrum, equals to zero near flat surfaces due to symmetry with respect to positive and negative components of the spatial spectrum. This symmetry can be broken by a mutual lateral movement of bodies. In this case appears the contact-free van der Waals or quantum friction [1]. The lateral drag forces appear nearby inhomogeneities of a surface, such as corrugations. However, these forces, affecting a particle, have a local action and a propulsion length is limited with a period and cause rather a displacement than a movement of a particle. A lateral propulsion force, exerted on an anisotropic particle, with a theoretically unlimited length of action, was predicted recently by Müller and Krüger [2]. In this case anisotropic particle must be in a thermal nonequilibrium with an absorbing plate.

We predict a novel effect which is appearance of lateral radiative forces near a smooths unmoved slab of absorbing anisotropic medium. The optical axis must be tilted to boundaries of the slab. Interaction between such a slab and another body, provided via TM waves, exciting by fluctuating sources, takes place even under the thermal equilibrium. Idea of this work has the following motivation. If an open slab of absorbing medium is anisotropic and the anisotropy axis is tilted to interface, absorption of the TM-polarized wave, incident on the slab, is different for the positive and negative incident angles despite the reflection is the same [3]. And vice versa, spatial spectra of fluctuating electromagnetic fields are different for the positive and negative wave vector components that results in appearance of lateral radiative forces. This effect occurs in any absorbing anisotropic media, but it may be especially noticeable with hyperbolic metamaterials.

We solved the boundary-value problem for electromagnetic waves, excited by point-like fluctuating currents within a finite-thickness slab of asymmetric anisotropic medium. Green's function for an open finite-thickness slab with the tilted anisotropy axis has been derived. Then, by using the fluctuation-dissipation theorem, components of the Poynting vector and other field bilinear forms, responsible for radiative forces, have been found. As an example, radiative forces, acting on a small particle, have been calculated in a dipole approximation. Amazing effect of the particle movement along the slab interface under the Casimir forces is demonstrated.

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Anisotropy of metamaterials induced by spatial dispersion

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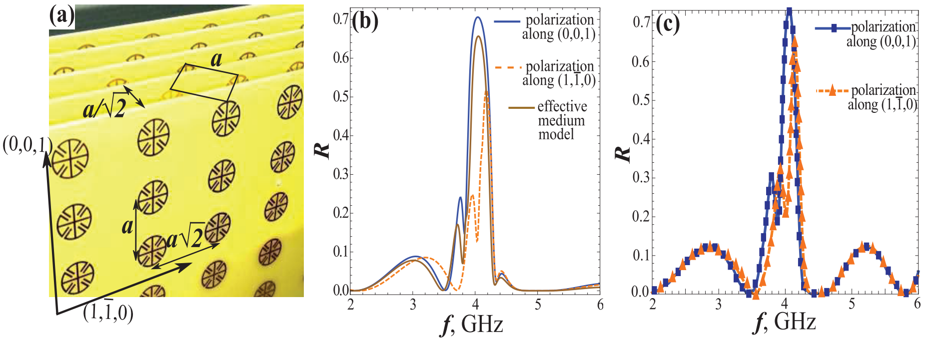
In the metamaterial literature there were reported various designs of isotropic metamaterials composed of plasmonic, dielectric or magnetodielectric particles (e.g. Ref. [1]). The response of such structures is believed to be isotropic due to the isotropic meta-atoms as well as high symmetry of the lattice. However, it turns out that the isotropy of such metamaterials can be violated due to spatial dispersion effects. This phenomenon known as spatial-dispersion-induced birefringence is already studied for natural materials [2]. Spatial-dispersion-induced birefringence is characterized by the difference of effective refractive indices for $(1,\bar{1},0)$ and $(0,0,1)$-polarized eigenmodes, $\Delta n = n_{1\bar{1}0} - n_{001}$, and for typical natural crystals $|\Delta n| \leq 5 \cdot 10^{-5}$. On the other hand, spatial-dispersion-induced birefringence has not been inverstigated in metamaterials so far.

Our recent theoretical studies [3] reveal that in the case of metamaterials spatial dispersion effects are extremely pronounced leading to the noticeable anisotropy of the structure in the vicinity of the individual inclusion resonance. In order to validate our theoretical predictions we fabricated a structure with the cubic lattice depicted in Fig. 1a and measured the reflection coefficients under the normal incidence for the waves polarized along $(1,\bar{1},0)$ and $(0,0,1)$ directions. Importantly, in the case of normal incidence polarization perpendicular to PC boards is not excited. Therefore, in this special case planar particles perfectly mimic isotropic inclusions.



Whereas local effective medium model predicts that reflection coefficients for both polarizations are essentially the same, our theoretical approach (Fig. 1b) as well as experimental results (Fig. 1c) demonstrate the difference between the reflection coefficients. This serves as the direct evidence of the structure anisotropy induced by spatial dispersion. From the measured reflectance we estimate the magnitude of spatial-dispersion-induced birefringence which reaches $\Delta n = -0.13$ exceeding the corresponding value for natural crystals at least by three orders of magnitude.

Fig. 1: Observation of spatial-dispersion-induced birefringence in metamaterials. (a) The experimental sample with the lattice period $a = 16.3$ mm. (b) Theoretical results for reflectance. (c) Experimental results for reflectance.

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Diamagnetism due to toroidal response

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Metamaterials with toroidal dipolar response demonstrate a number of special properties such as negative refraction and cloaking, strongly localized fields and high Q- factor. We are interested in another property of toroidal metamaterials diamagnetism caused by toroidal moment in a particular metamolecule. To demonstrate diamagnetic excitation in toroidal metamaterials we suggested metamaterials based on a special structure of metamolecules . They consist of two types of metamolecules separated by some space.One of them concentrates magnetic field due to toroidal and electric dipolar modes in metamolecule, another one electric field interfered toroidal and electric dipole. Combined together, they support coupled diamagnetic response with separated strongly concentrated electric and magnetic fields. We discuss this effect theoretically and shown diamagnetic response due to toroidal excitation.

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Beyond superabsorption: how to design efficient absorption of light by nanoparticles

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Nanoparticles have a fundamental limit as to how much light they can absorb. This limit is based on the finite number of modes excited in the nanoparticle at a given wavelength and maximum absorption capacity per mode. The enhanced absorption can be achieved when each mode supported by the nanopartice absorbs light up to the maximum capacity. Using stochastic optimization algorithm, we design multilayer nanoparticles, in which we can make several resonant modes overlap at the same frequency resulting in *superabsorption*. We further introduce the *efficiency of the absorption* for a nanoparticle, which is the absorption normalized by the physical size of the particle, and show [1] that efficient absorbers are not always operating in the superabsorbing regime.

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Solitary waves in chains of silicon nanoparticles

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Modern tendency to replace the components of electronic integrated circuits with optical ones by means of minituarizing the latter requires very small interconnecting elements — relatively short waveguides with subwavelength cross-section sizes. One of the promising realizations of such waveguides is the chain of dielectric nanoparticles with high refractive index, e.g. silicon nanoparticles [1,2]. Linear properties of silicon nanoparticles and structures composed of them were extensively studied in the last several years. However, despite the apparent interest in their nonlinear properties, quite a few works were addressing this issue [3-5]. In these studies either nonlinear scattering of light by silicon nanopartices and structures or third-harmonic generation was studied.

Here we consider theoretically the pulse propagation in the waveguide composed of silicon nanoparticles with nonlinear Kerr-like response. We show that despite the low quality factor of a single silicon nanoparticle, very high group velocity dispersion of the nanoparticle waveguide, the compensation of pulse broadening with nonlinearity in the dielectric discrete waveguide can be achieved at the lengths of several tens of micrometers in optical frequency range. This is possible to achieve by exploiting the properties of the silicon nanodisks with the parameters providing close magnetic and electric dipole resonance frequencies. In contrast to the chain of silicon nanospheres having negative dispersion $\omega'' = d^2\omega/d\beta^2$ at all frequencies, the chain of appropriately arranged nanodisks has positive ω'' in a certain frequency range, i.e. it has the same sign as nonlinear refractive index of silicon, which allows to obtain a soliton in nanodisks waveguide at realistic level of intensities $\lesssim 5$ GW/cm^2.

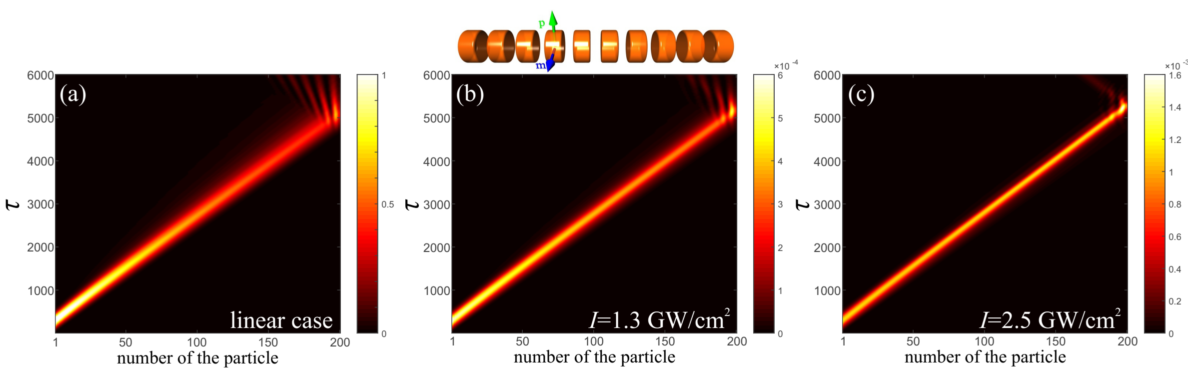

Fig. 1: Dynamics of the 100 fs pulse propagating in the chain of nanodisks (a) in the linear regime, (b,c) in the nonlinear regime with intensities (b) $I = 1.3$ GW/cm^2, (c) $I = 2.5$ GW/cm^2.

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Optical Forces and Metamaterials

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Optical manipulation and control of nano- and micro-scale particles is vital for development of next generation of lab-on-a-chip opto-fluidic devices and sensing applications as well as for advanced nano-opto-mechanical systems for photonics. One of the primarily goals of optical manipulation research is to reduce the overall power of a trapping beam and to achieve stiff and highly localized potential profiles of light. A promising approach for optical tweezers with sub-diffraction light confinement is to utilize plasmonic nanostructures [1,2]. Highly-confined extraordinary modes of the hyperbolic metamaterial slab can be excited via scattering of external illumination on an inhomogeneity situated on the slabs interface (Figure 1a).

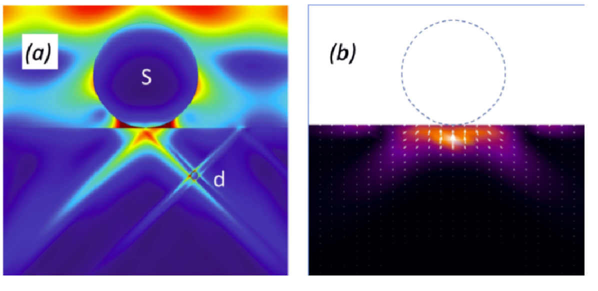

Fig. 1: (a) Typical intensity distribution created by surface scatterer S and a small dipolar particle d inside metamaterial slab; (b) Linear density of optical force inside metamaterial slab (arbitrary units) as a function of dipolar particle coordinates. The magnitude of the force density is shown with color, while the direction of the force is represented by white arrows..

The example of numerically calculated optical linear force densities on a dipolar particle is shown in Fig. 1b. Calculations performed with Finite Elements Method (Comsol Multiphysics) for both metallic and dielectric particles show that particles move to the upper interface of the metamaterial slab, i.e. against the light propagation direction [4].

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Submicron-micron size 3D features artificially created by tightly focused laser pulse for plasmonics applications

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Illumination by laser is very widely used as a tool for modification of a target. Here we consider the practically important case when a pulse is short and illuminated area is small. Studies of the case with a short pulse and a small spot begin and continue in papers by Chichkov, Nakata and others, see [1] and the references cited therein. Structures created in this way are used in nanoplasmonics, laser induced forward transfer (LIFT, laser printing) technologies, in metaoptics, advanced solar cells, for fabrication of photon crystals, hydrophobic surfaces, as well as for surface-enhanced fluorescence and Raman spectroscopy (SERS) applications, and fabrication of nanoparticles.

Tightly focused diffraction limited optical laser pulse illuminates a small spot at a surface of a thin metal film mounted upon a dielectric or semiconductor support (substrate). Usually 30-60 nm thick gold film is used. Film mechanically separates from substrate and form a cupola like bump in a rather narrow range of absorbed fluences, see Fig. 1. Below this range of fluences the deformations inside the laser spot are negligible. While above this range the hole remains in a film in the irradiated spot. The paper presents physical model starting from absorption and two-temperature state and including, first, description of conductive redistribution of absorbed heat, melting, hydrodynamics of strong three-dimensional deformations of a moving film, and, second, freezing of molten metal. Figure 1 presents this sequence of events.

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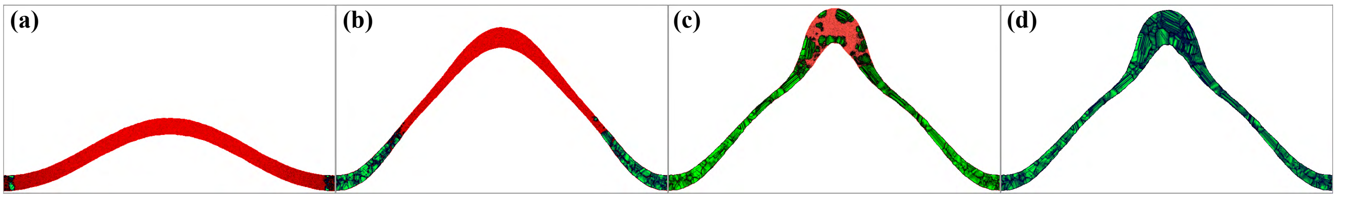

Fig. 1: 3D blistering of a gold film placed on a glass substrate (matter of the substrate isn't shown). This is the lateral view of the cross section going through the vertical axis of rotation (approximately axisymmetric expansion). Evolution after short illumination: (a) melting and kick off from substrate, red is liquid gold, green is crystal; (b) inflation of a cupola like bump, together with gradual freezing propagating from the lateral sides into the liquid filling the central part of a cupola, cooling is caused by a heat transfer from the hot bump to the lateral part of a cold film remaining on a substrate. Important is the capillary deceleration of motion up; (c) stopping of motion up and the final stage freezing; (d) total freezing and stop of cupola. It is possible to produce diverse 3D features using different illumination and target conditions.

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Controlling the assembly and welding of gold nanorods by means of femtosecond laser pulses

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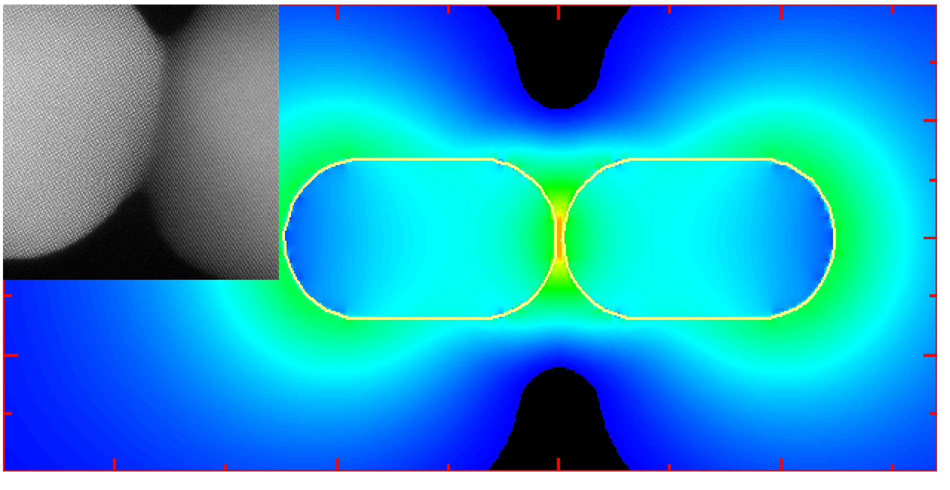
Directed assembly of gold nanorods through the use of dithiolated molecular linkers is one of the most efficient methodologies for the morphologically controlled tip-to-tip assembly of this type of anisotropic nanocrystals. In a direct analogy to molecular polymerization synthesis, this process is, however, characterized by difficulties in chain-growth control over nanoparticle oligomers. We have devised a light-controlled synthetic procedure that allows obtaining selected plasmonic oligomers, in high yield and with reaction times in the scale of minutes, by irradiation with low fluence near-infrared (NIR) femtosecond laser pulses. Selective inhibition of the formation of gold nanorod n-mers (trimers) with a longitudinal localized surface plasmon in resonance with a 800 nm Ti:sapphire laser, allowed efficient trapping of the (n1)-mers (dimers) by hot spot mediated photothermal decomposition of the interparticle molecular linkers. Laser irradiation at higher energies produced near-field enhancement at the interparticle gaps, which is large enough to melt gold nanorod tips, offering a new pathway toward tip-to-tip welding of gold nanorod oligomers with a plasmonic response at the NIR. Thorough optical and electron microscopy characterization indicates that plasmonic oligomers can be selectively trapped and welded, which has been analyzed in terms of a model that predicts with reasonable accuracy the relative concentrations of the main plasmonic species.



Protein temperature and conformation control at the nanoscale

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Direct observation of thermal-induced molecular interactions or single molecular events at the nanoscale remains challenge in biophysics. Key physical (luminescent or circular dichroism) techniques provide this information with low thermal and spatial resolution. Here we propose a conceptually new approach based on Raman scattering to observe molecular events with simultaneous control of the temperature at the nanoscale: the use of single silicon nanoparticle as a marker gives information about local temperature due to its thermal dependent Raman scattering while Raman scattering of surrounding molecules provides information about molecule state. We demonstrate this concept for a well-studied process of thermal induced unfolding of a small globular protein and achieve 0.4 K thermal and sub-diffraction ($\sim$100 nm) spatial resolution.

Synthesis and study of GaN nanowires and nanotubes on Si

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In this work we study growth and properties of semiconductor GaN nanowires (NWs) on Si(111) substrates synthesized by means of plasma enhanced molecular beam epitaxy (PAMBE) using AlN thin mask layer. We first investigate the influence of growth conditions on NWs array morphology to show that the substrate temperature and Ga flux affect both the surface density and growth rate of the synthesized array. It was determined that at a fixed flux of nitrogen equal to 1.3 cm^3/min the maximum growth rate of NWs is $\approx$ 38 nm/h at a substrate temperature 800 degrees Celsius. It was also found that the growth rate of NWs on the substrates treated with the oxide removal procedure is half the growth rate on substrates covered with oxide, while NWs surface density is twice higher. We do also study dependence of NWs doping level on Si doping flux. In addition, we have shown the possibility of synthesizing GaN nanotubes using high intensity Si doping flux.

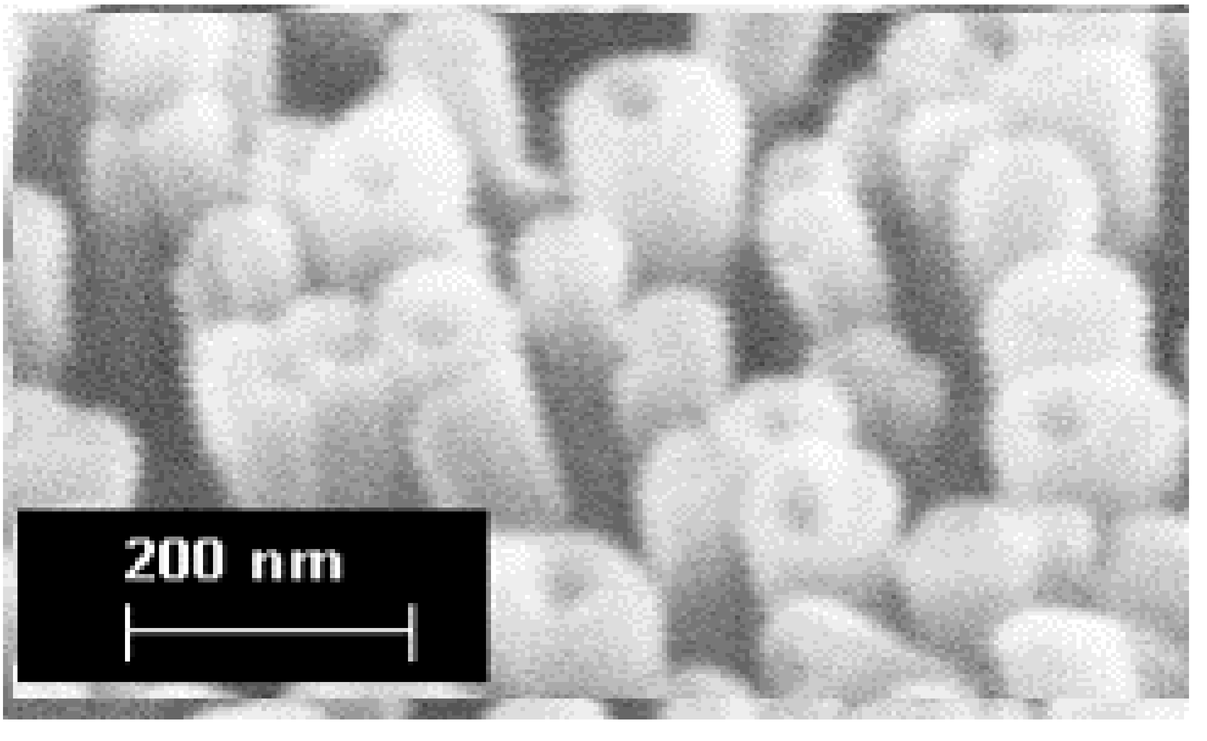

Fig. 1: GaN nanotubes grown by means of PAMBE on Si (111) substrate using high-intensity Si-doping flux

Manipulation of excitons in metal-organic van der Waals crystals at room temperature

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van der Waals crystals have emerged as conceptually new structures for efficient manipulation of exciton states. Here, we demonstrate that synergistic combination of organic and inorganic nature in the crystal paves the way for incredible manipulation of excitons by light at room temperature. As a model material we use metal-organic framework (MOF) with layered van der Waals structure that possesses two types of robust excitons (inter- and intra-layer). Optical density of each exciton state can be independently manipulated via light-induced reversible crystal disordering, as well as photoexcitation under ultrafast or low-intensity continuous irradiation. We reveal that the inter-layer exciton state is much more sensitive to the light manipulation and causes nonlinear dramatic and reversible changing of optical properties of MOFs from ultrashort (100-fs) to extremely long (48 hours) time.

Quantum-mechanical modeling of spatial and electronic structure of Zn-based metal-organic framework

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Herein, we report results of ab-initio calculations of the spatial and electronic structure of the new Zn-based metal-organic framework (MOF-ZnO) - $[Zn_2(TBAPy)(H_2O)_2 \cdot 3.5DEF]_n$, where TBAPy = 1,3,6,8-tetrakis(p-benzoate)pyrene. Crystals of this MOF-ZnO were obtained using a new method based on slow diffusion conditions created by the flow gradient in liquids separated by a gas layer [1].

First, the optimization of geometry of the MOF-ZnO unit cell are performed by semi-empirical method PM7[2]. The remarkable agreement of calculated results with known experimental XRD data [1] are obtained. Second, the electronic structure and molecular orbitals wave functions are calculated with the plane-wave basis set and density functional theory. The Perdew, Burke and Ernzerhof (PBE) exchange-correlation functional are used [3]. All the ab-initio computations presented in this work are performed with the Quantum ESPRESSO (QE) package [4].

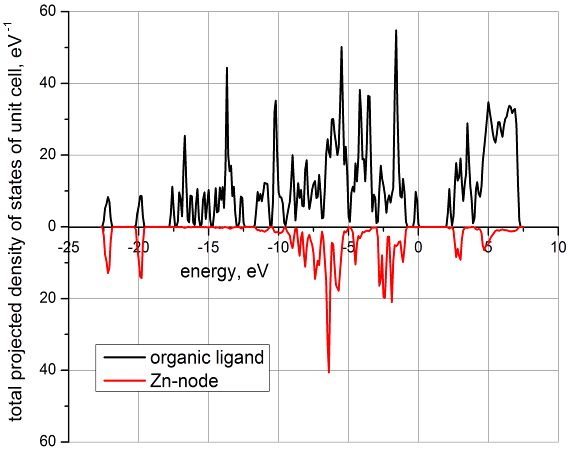

Fig. 1: Calculated density of states.

Figure 1 shows calculated projected density of states (PDOS) spectrum of MOF-ZnO. The calculations of the PDOS are performed with the help of auxiliary post-processing program "dos" of QE package. Obtained PDOS for each atom have been divided into two groups: for atoms which belong to Zn-node and to the organic ligand. This makes it possible to analyse the optical properties of MOF-ZnO and to explain the nature of the excitonic peak in its absorption spectrum.

IIV and RGP acknowledge support from Russia's Federal Program "Scientific and Educational Manpower for Innovative Russia" (grant no RFMEFI58715X0020), RGP acknowledges support by Rannis Project "BOFEHYSS" and EU RISE Project "CoExAN 644076".

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Controlling circular polarization of light emitted by quantum dots and wells using chiral photonic crystal slabs

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Advances in nanoscale fabrication have made it possible to realize artificial photonic structures with desired symmetry and density of the environmentally allowed electromagnetic modes, which allows controlling the spontaneous emission rate of emitted light, its radiation pattern, and direction. The fabrication of chiral nanostructures from achiral semiconductors opens the possibility to control the polarization of light of semiconductor emitters.[1].

We discuss the polarization properties of light emitted by quantum dots (QDs) or wells (QWs) that are embedded in chiral photonic crystal (CPC) structures made of achiral planar GaAs waveguides and/or microcavities (MCs) by fabricating a square lattice of unit cells consisting of four rectangular pillars, each rotated by 90^o with respect to its nearest neighbors via electron-beam lithography and reactive ion etching. The unit cell has broken in-plane mirror symmetry but possess a fourfold rotational axis. Based on the reciprocity and symmetry analysis, we show that the CPC slab works as a "half-wave" plate, exploring the Fabry-Perot interference between the propagating modes in CPC structure, to reach circular polarization close to 100%.

The fabricated structure with InAs QDs inside a GaAs waveguide has demonstrated a circularly polarized QD emission with ρ_c up to 81% and up to 96% if the unpolarized background due to structure imperfection is removed, which is close to theoretical value of 98%[2]. The emission is shown to correspond to the excitation by QDs of the $(\pm 2, \pm 2)$ Bragg resonance of quasiguided modes in the waveguide.

The use of high-Q planar MCs with QWs in the active region instead of waveguides opens the possibility to obtain the circularly polarized stimulated emission. The MC with incorporated GaAs QWs and CPC slab fabricated by nanolithography and dry etching of 4.5 pairs of GaAs/AlAs layers of the upper mirror has demonstrated the lasing emission with high both $\rho_c \approx 0.8$ and $\rho_{lin} \approx 0.5$, resulting in a total $\rho = (\rho_c^2 + \rho_{lin}^2)^{1/2} \approx 0.95$. The linear polarization seems to be due to the lowered symmetry of unit cells in the fabricated structure.

Thus the nanotechnology allows fabricating CPC nanostructures with embedded light emitting QDs and/or QWs to realize the light emitters including lasers with a high ρ_c at zero magnetic field. The advantage of CPC structures is the giant chirality allowing fabrication of very thin, of the order of λ, half-wave plates which, in addition, have in-plane rotational isotropy due to the C4 symmetry.

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Spin chaos in cavity-polariton condensates

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Recent advances in nanophotonics have brought about coherent light sources with chaotic circular polarization [1]. Today, however, only a low-dimensional chaotic evolution of optical spin is achieved experimentally. In this theoretical report we address the problem of making spin of light reveal a *spatiotemporal* chaos, similar to turbulent fluids with high-dimensional chaotic attractors. We have found that light with such properties can be emitted by the system of cavity polaritons, half-light half-matter excitations in microcavities [2].

It has long been accepted that chaotic polariton states are feasible only in laterally inhomogeneous structures similar to Josephson junctions. Here we report a mechanism lifting such limitation. We consider an internally homogeneous polariton system under resonant plane-wave optical driving and show that its well-known multistable behavior can be turned into spatiotemporal deterministic chaos. The key point is the spontaneous breakdown of spin symmetry [3–5], which brings about an extreme sensitivity to fluctuations. The scattering into Bogolyubov modes acts to close the cycle and triggers an infinite series of spin switches. This mechanism is fundamental; being independent of the potential landscape or shape of the pump wave, it is expected to take place in arbitrarily sized planar microcavities.

We arrive at the conclusion that cavities with strong exciton-photon coupling can serve as significantly advanced all-optical counterparts of chaotic laser diodes. In particular, they operate on the picosecond ("photonic") rather than nanosecond ("electronic") timescale and also exhibit spatiotemporal spin chaos, a novel optical feature. This opens up the way for spin modulation of light on the scale of picoseconds and microns.

The work was supported by the RFBR (grant No. 16-02-01172) and the Russian Science Foundation (grant No. 14-12-01372).

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Stochastic conversion processes in bosonic condensate of exciton-polaritons

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In this work we present theoretical description of stochastic exciton-photon transitions in bosonic condensate of exciton polaritons. Exciton-polaritons are two-dimensional half-light half-matter quasi-particles with bosonic statistics. Each individual polariton can be described as a superposition state of an exciton and a photon. Based on the dual nature of exciton-polaritons some hidden parameter $1/\tau_{xc}$ can be introduced as characteristic of the rate of stochastic exciton-photon and photon-exciton conversions. The system of exciton polaritons is described by the density matrix, which evolves according to Bloch equation, while the role of the stochastic conversions is understood in terms of several exciton-photon correlators. In Figure 1 we demonstrate the time evolution of several diagonal elements $P(n_a, n_b, t)$ of the density matrix for the initial coherent state, where n_a and n_b are the average numbers of excitons and photons respectively.

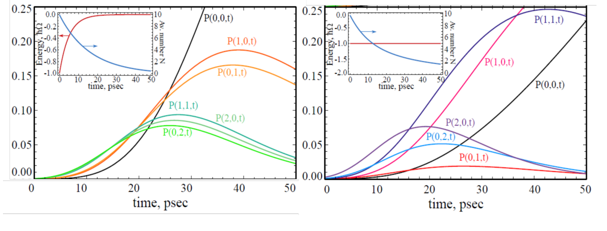

Fig. 1: Evolution of diagonal elements $P(n_a, n_b, t)$ and the average number of particles N as well as the energy per particle on insets. The panel (a) corresponds to the finite time of the exciton-photon conversion $\tau_{xc} = 5$ ps, while the behavior in the absence of stochastic conversion is shown in the panel (b). The polariton condensate is initially in the coherent state with $N = 10$. The life-times of excitons and photons are $\tau_x = 40$ps and $\tau_c = 10$ps.

In the panel (a) the stochastic conversion time is finite while in the panel (b) the stochastic process is neglect. Here the presence of the exciton-photon conversion is evident in similar behaviour of the density matrix elements $P(n_a, n_b, t) = P(n_b, n_a, t)$ if $t > \tau_{xc}$ in the panel (a) while there is an asymmetric behaviour of the density matrix elements for $\tau_{xc} \to \infty$ caused by the different lifetimes of excitons and photons in the panel (b). In addition we analyze the average number of particles and the energy time evolutions, which have different behaviours in dependence on precense or absence of the stochastic exciton-photon conversion processes. These evolutions are presented in inserts of Figure 1.

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Nonlinear topological excitations in polaritonic kagome lattice

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Topological properties of matter are among current trends in theoretical physics. While the common signatures of topological order such as Berry curvature and Chern numbers are well studied in non-interacting linear systems, many body interactions can substantially modify the underlying physics and result in emergence of qualitatively new phenomena. It is therefore of fundamental importance to study the interplay of topology and interactions in quantum systems. Exciton-polaritons in microcavities provide a unique laboratory for study of such phenomena. Being hybrid light-matter particles exciton-polaritons possess extremely small effective mass inherited from their photonic component and can efficiently interact with each other. Spin-dependent polariton-polariton interactions in microcavities result in nonlinear response which are orders of magnitude stronger then in other types of optical systems. Additional advantage of polariton systems is provided by the ability to control their properties via external electric and magnetic fields. Due to their unique property of combining characteristics of both light and matter, exciton-polaritons offer exciting perspectives for simulating topological phases of condensed matter, which are either unreachable or require extreme conditions such as high pressure and very low temperature.

In this work we study exciton-polaritons confined in microcavity pillars arranged into a kagome lattice. TE-TM splitting in the tunnel coupling of microcavity pillars leads to emergence of the effective spin-orbit interaction comprising the Dresselhaus and Rashba terms. The spin-orbit interaction combined with the time-reversal symmetry-breaking due to the applied magnetic field leads to nontrivial topological properties of polaritonic wavefunction. These are manifested in appearance of topological edge states propagating along the boundary. Such states are analogs of the edge states arising in topological insulators. We study the effect of nonlinear interactions on topological properties of polaritons and observe formation of bright and dark edge state solitons.

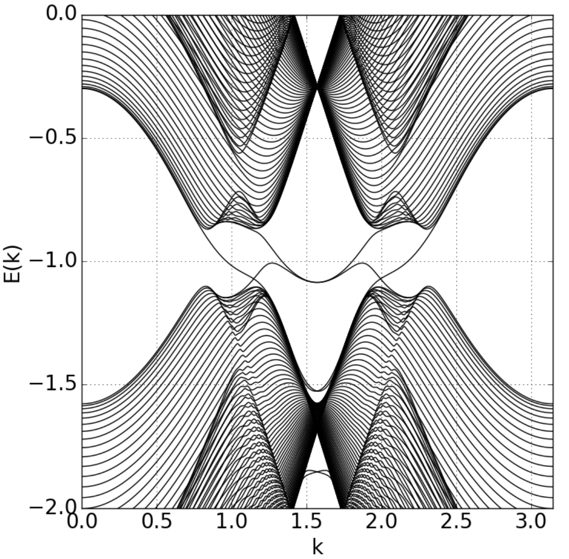

Fig. 1: Dispersion of topological edge states in exciton-polariton kagome lattice.

Thermophotovoltaic systems enhanced by nanowires

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Recently we theoretically have shown that a thermophotovoltaic (TPV) system enhanced by a wire medium (WM) of tungsten nanowires opens the door to a prospective microgap thermophotovoltaics allowing huge values of the electric output for standard temperatures of the emitter [1]. In the present work we reveal (still theoretically) that similar results are achievable for emitters of relatively low temperatures. The suggested system comprises an array of parallel metal (e.g. golden) nanowires grown on top of a photovoltaic (PV) semiconductor and standing free in the vacuum gap between the host dielectric layer and the emitter, so that their ends are sufficiently close to the emitting surface. Due to the resonant near-field coupling between this WM and the emitter and due to the optimized layered structure of the whole system, the strongly super-Planckian radiative heat flux of resonant nature is engineered for a relatively cool (500°C) emitter of heavily doped (minor carrier density 10^{20} cm^{-3}) crystal silicon. The radiative heat transfer turns out to be very narrow-band and its maximum is blue-shifted with respect to the maximum of the black-body radiation on the same temperature. We have obtained the electric output $\mathcal{P}_{\rm elec} = 26\,{\rm kW/m^2}$ which is only twice lower than that obtained in [1] for the emitter of temperature 2000°C. This result is 50-fold power out put of the thermoelectric analogue operating at the same temperature. Values $W_{\rm h}$, $W_{\rm s}$, $W_{\rm g}$ shown in Fig. 1 (a) were optimized, $\varepsilon = 2.25$ (glass), and $W_{\rm p}$, $W_{\rm d}$, $W_{\rm n}$ were taken typical for InSb PV cells. Besides of the working temperature, one may dramatically decrease all the costs replacing the heavily doped c-Si by graphite and replacing the microgap by an intermediate material (intrinsic silicon) as shown in Fig. 1(b). Here the silicon layer thickness D is a macroscopic value allowing the thermal management of the PV cell. The gain due to the near-field coupling of the cold and hot sides is replaced by the gain granted by silicon ($\varepsilon \approx 12$ in the mid-IR range). Nanowires are on the cold side and play the role of the frequency filter. Conductive heat transfer across the structure is much lower than the radiative heat transfer in the operation band. If $D > 1$ cm, the temperature of the PV layer will not exceed 100°C with a simple tap water cooling frame. In our preliminary calculations, this generator beats the power output of the thermoelectric analogue nearly 20 times.

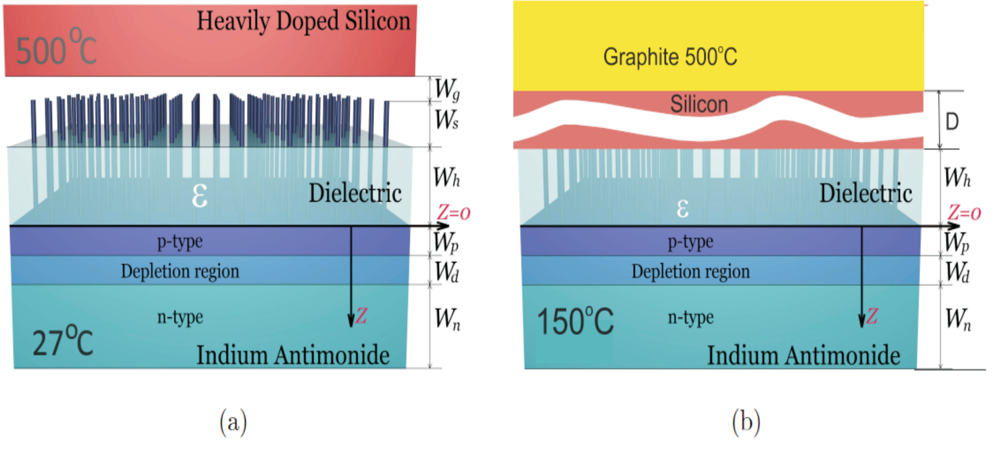

Figure 1: New TPV generators with cold nanowires: (a) – a microgap one, (b) – a gap-free one.

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Manipulating the electromagnetic fields using wire media

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Metamaterials performed as lattices of aligned metallic wires with subwavelength periods have been actively studied for a wide range of applications during last years. An important property of wire media (WM) is their strong spatial dispersion, which enables many interesting electromagnetic effects. Recently, in our group we studied theoretically and experimentally enhancement of power radiated by small (dipole) sources submerged into WM [1]. This enhancement results from two effects: the transformation of evanescent waves into propagating modes and the so-called hyperlensing [1].

If a finite-size structure of parallel metallic wires comprises an embedded dipole source, the radiation to free space is enhanced only within quite narrow frequency bands. Besides these Fabry-Perot resonances the enhancement is absent because the internal reflection blocks the radiation and in the system with negligible absorption restricts it on the same level as the radiation of the same dipole in the absence of the wire medium [1, 2]. However, if the interfaces of the slab are modified e.g. by closely located dielectric layers the internal reflection can dramatically reduce. In this report we demonstrate broadband transfer of power through a WM slab connecting two waveguides [2]. Here the waveguide open end plays the role of a dielectric interface. Next, we present two other WM structures which allow broadband enhancement of radiation from subwavelength sources. The first one is a WM hyperlens of truncated conical shape, which grants this enhancement to the sources located near its apex. Another one is the so-called irregular WM brush which offers a similar enhancement to the sources located in a large area because the overall shape of the sample is a flat layer. All our claims are accompanied by extensive simulations and validated experimentally.

We believe that the presented results are important for many prospective applications. WM can be realized in many frequency ranges, and in all of them have basically the same electromagnetic properties. For example, the revealed broadband power transfer in WM slabs though was confirmed at microwaves is a conceptual confirmation of the idea of enhanced radiative heat transfer through a thermophotovoltaic microcavity filled with nanowires operating in the mid infrared frequency band. Our structures can find applications from radio frequencies (imaging microwaves noises in electronic chips) to ultrafast (radiative) cooling of hot microscopic objects, which is a challenging problem of nanophotonics.

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Full broadband absorption of perovskite solar cells with plasmonic nanoparticles

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A novel regime of absorbtion in a thin plasmonic layer corresponds to a collective mode of an array of densely packed plasmonic nanospheres. In our theoretical study we show that this regime results in the absorption of the incident light in the semiconductor material hosting plasmonic nanospheres, whereas the absorption in the metal is very small. The regime survives when the uniform host layer is replaced by a practical photovoltaic cell. Moreover, this regime is compatible with both metal-backed variant of the cell and its semitransparent variant with a dielectric substrate. Negligible parasitic losses, variety of design solutions and reasonable operational band make our plasmonic absorbers promising for photovoltaic applications.

Some regular nanostructures (plasmonic grids or photonic crystals) may convert an incident plane wave into waveguide modes of the subwavelength thin PV layer mimicking in this way an optical facet [1]. A usual facet has optically large teeth and cannot be directly used for exciting a so thin film waveguide due to the so-called Yablonovitch limit [2]. In our work we show that the similar subwavelength light concentration in a thin layer of PV host material is achievable for an array of densely packed silver nanospheres, perhaps covered by a thin dielectric shell. Earlier this regime (with concentration of electric field beyond the metal elements)was revealed only for arrays of complex nanoantennas. Here we exploit a collective resonance of the nanospherical array, at which the structure possesses both electric and magnetic responses. The dense packaging of spheres allows their self-assembly that should simplify the fabrication and makes our design fully practical.

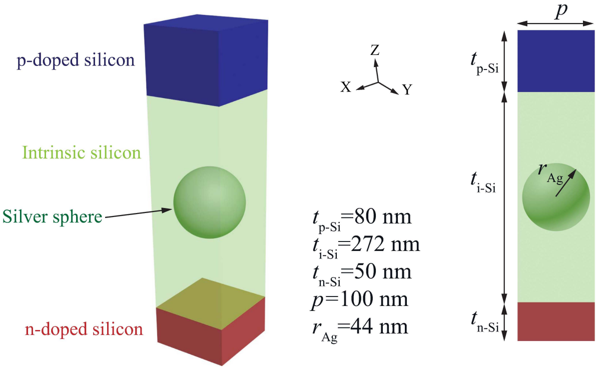

Figure 1: The p-i-n structure with Ag spheres in the intrinsic a-Si.

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Mutli-type particle layer enhanced absorption for PV applications

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Nanoparticle assisted light harvesting in photovoltaic devices mostly exploits collective and scattering properties of nanostructured front surface layers [1, 2]. Regular particle arrays typically show narrow spectral resonances, and broadband total absorption can be achieved combining different particle sizes and shapes to create a spectral overlap of resonances in the regular array.

We discuss dielectric and plasmonic particle layers as nanostructured front layers for 3rd generation photovoltaic devices made of unit cells that include more than a single particle type. We demonstrate that already using two differently sized nanodisks of the same material can increase not only the overall absorption but also the absorption at the active device level A_{act}, corrected by losses in the particle array itself. This quantity is difficult to assess in experiments. Efficiency enhancement in terms of short circuit current and average absorbance is studied as a function of geometry parameters, where we observe enhancement factors of up to and above 30%.

A rigorous plane-wave method is used [3, 4] to investigate such multi-type particle layers placed on top of a Si wafer and a glass substrate, see Fig. 1. We study the effect of mixing up to four different materials and particle sizes, including aspects of disk height. While the combination of different materials is easily possible in this theoretical method, it is difficult to achieve in experiments, however fabrication of such samples with lithographic methods is feasible.

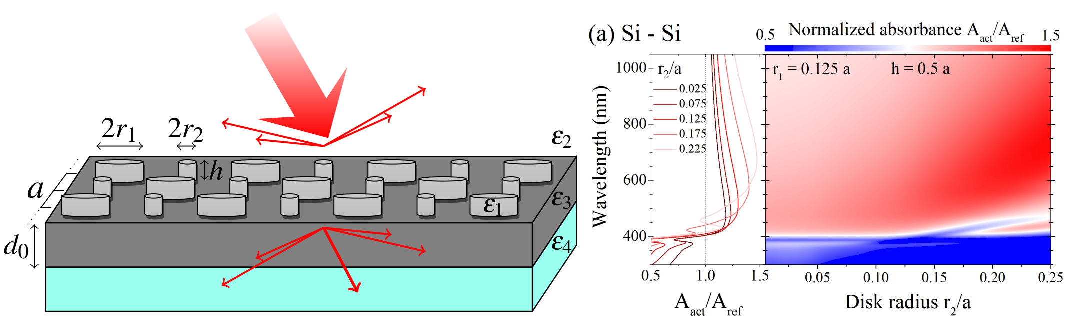

Fig. 1: Illustration of the base geometry: a photo-active Si-wafer (thickness d_0, permittivity $\epsilon_3(\omega)$) on a glass substrate ($\epsilon_4(\omega)$). A photonic crystal structure composed of disk particles with equal height h, periodicity a, radii r_1, r_2 and space-modulated permittivity $\epsilon_1(\vec{r}, \omega)$ lies on top. (left) 2-type solar cells made of Si disks using different disk radii r_2 while keeping constant height $h = 100$nm and $r_1 = 25$nm. The curves plotted on the left hand side of the contour show spectra at specific size combinations. (right)

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Optical domino-modes in arrays of metal nanostrips and their application in photovoltaics

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In thin-film solar cells (TFSCs), the so-called light-trapping structures (LTSs) replace conventional anti-reflecting coatings (ARCs) because ARCs cannot prevent the solar light transmission through so thin layers. This transmission results in the energy loss and harmful heating of the photovoltaic layer from the bottom electrode [1]. Many suggestions of LTSs are based on nanoantennas (NAs) [2]. NAs forming an LTS convert the incident solar light into a set of hot spots, increasing the useful absorption and preventing the parasitic transmission. Researchers have put significant efforts into creation of NAs, which create the hot spots beyond their own volume in order to avoid a harmful dissipation of the solar energy in NAs.

Another key point of light-trapping is the bandwidth. Since the solar light has a very broad frequency spectrum, in order to be efficient for TFSCs, the NAs have to be multi-resonant. One of the best known theoretical results for such LTSs were reported in works [3, 4]. It was claimed in [3, 4] that these NAs exploit collective modes of the NA array called *leaky domino-modes*. In this paper, we show that the resonances of absorption in our arrays [3, 4] are really collective oscillations, corresponding to the leaky modes and determined by the electromagnetic interaction of elements [5].

In this work, we have investigated the leaky modes of domino nanoparticle arrays. Our arrays possess advantageous electromagnetic interaction between adjacent metal elements which results in a set of multipole resonances. These resonances overlap and form a broad resonance band. This is valid for both transversal and longitudinal polarizations of domino-elements. The density of these modes increases when the elements are located on a substrate. This frequency region does not contain dipole plasmon modes, in which the absorption occurs inside the metal elements. Such a phenomenon is very unusual for the optics of metal structures.

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Light trapping in metamaterial thermal black holes and wormholes

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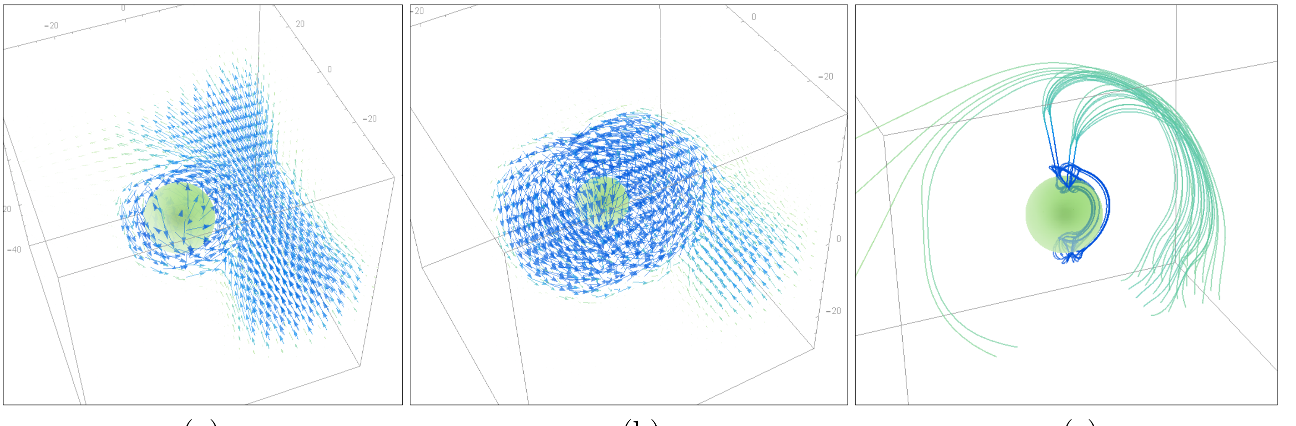
The metamaterial (MM) thermal black hole (TBH) is a macroscopic object with radius $a \gg \lambda$ whose effective absorption cross section at the wavelength λ is much greater than the geometric cross section πa^2. The MM TBH can be realized as a MM sphere with parameters

$$\varepsilon(r) = -\frac{\varepsilon_0 a^2}{r^2}(1 - i|\tan\delta|), \quad \mu(r) = -\frac{\mu_0 a^2}{r^2}(1 - i|\tan\delta|), \tag{1}$$

where $i = \sqrt{-1}$. When the loss tangent $\tan\delta \to 0$, the absorption cross section of the MM TBH can be made theoretically arbitrarily large: $\sigma_{\rm abs} \to \infty$, and thus this object can intercept *arbitrary* incident waves. In particular, it can intercept beams of light which are not directly incident on its surface (see Fig. 1). This peculiar property has important physical consequences such as super-Planckian far-field thermal emission from such objects [1] (this is why there is the word "thermal" in their name).



(a) (b) (c)

Fig. 1: Gaussian beam absorption and scattering by a MM TBH (green sphere) with finite core radius $0 < r_0 \ll a$ and loss tangent $|\tan\delta| \geq 0$. Panel (a): Distribution of the Poynting vector around the MM TBH for the case of $2\pi a/\lambda = 10$, $a/r_0 = 10$, and $\tan\delta = 10^{-10}$. Panel (b): Same as in (a), but for $2\pi a/\lambda = 5$, $a/r_0 = 5$, and $\tan\delta = 0$. Panel (c): Continuous energy flow lines for the case (b).

In practice, because the parameters (1) are divergent at $r = 0$, the singularity must be truncated in the core region $r \leq r_0$, which, together with finite value of $\tan\delta$, results in $\sigma_{\rm abs} < \infty$. Nevertheless, even with practically attainable parameters one may have $\sigma_{\rm abs} \gg \pi a^2$, so that unusual light-matter interaction phenomena are expected resulting from the peculiar behavior of such objects. For instance, effects resembling formation of accretion disks around a MM TBH, and light energy orbiting can be seen in Fig. 1. The electromagnetic energy circulating around the MM TBH gets eventually absorbed, after many rounds of entering and escaping the MM body [see Fig. 1 (c)]. These effects as well as the effects in novel MM structures such as MM *wormholes* will be considered with greater detail in the presentation.

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Stationary and dynamical states of polaritons in discrete systems

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The dynamics of polariton condensates in 1D array of polariton microcavities with incoherent pump is considered in tight-binding approximation. The order parameter in each of the cavity is characterized by complex amplitude ψ_m, the incoherent hot excitons is described by the density n_m. The dynamics of the polaritons and the excitons is governed by the set of coupled equations

$$i\partial_t \psi_m = \left(-\hat{D} - i\gamma_1 + in_m + |\psi_m|^2 + \alpha n_m\right)\psi_m, \tag{1}$$

$$\partial_t n_m = -\left(\gamma_2 + \beta|\psi_m|^2\right)n_m + P_m, \tag{2}$$

where $\hat{D}\psi = \sigma(\psi_{n+1} + \psi_{n-1} - 2\psi_n)$ is the operator of the discrete diffraction, γ_1 and γ_2 are the linear losses, α characterises the blue shift of the coherent polaritons, β accounts for the condensation of hot excitons, P_m is the pump intensity at m-th site.

The formation of different kind of coherent states in the case of localized pump is the focus point of the paper. It is found that depending of the parameters the condensation can go either into ground or into excited states. It is also demonstrated that complex dynamical states can form. In Fig. 1 the filed distributions and the corresponding spatial-temporal spectra are shown.

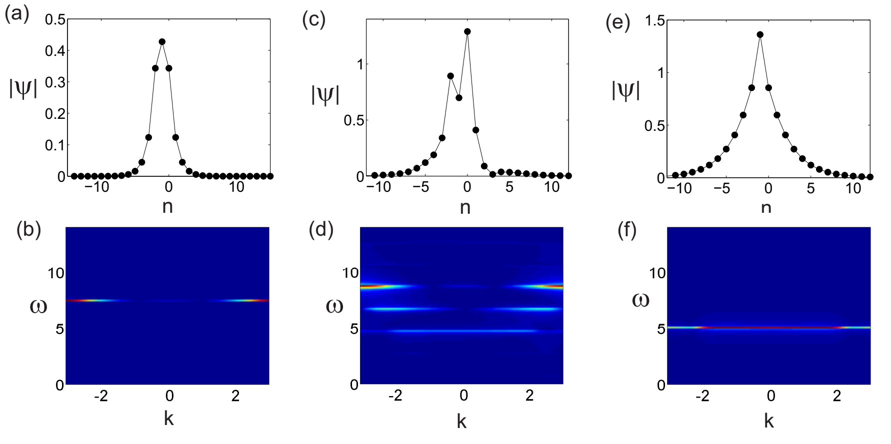

Fig. 1: Panels (a) and (b) show the field distributions and spatial-temporal spectrum for the case of three pumped sites, the pump is $P = 1.8$. Panels (c),(d) and (e),(f) show the same for the pumps $P = 4$ and $P = 4$. The other parameters are $\sigma = 1.5$, $\alpha = 1.8$, $\beta = 1.1$, $\gamma_1 = 1$, $\gamma_2 = 1.5$.

The theory qualitative explaining the observed phenomena is developed. It is also discussed how the reported results explains the formation of different states in the experiments on polariton condensation in semiconductor microcavities.

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Nonlinear dynamics and the band-structure of the exciton-polariton condensate in one-dimensional periodic lattices

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We present a comprehensive theoretical study of the nonlinear dynamics of the open-dissipative exciton-polariton condensate in a weak-contrast periodic one-dimensional structures. We consider condensate formed in the semiconductor microcavity by the nonresonant pump which is responsible for the formation of reservoir of incoherent excitons. The external periodic potential can be imposed, for instance, by the deposition of metal stripes on the microcavity surface [1] or by surface acoustical waves [2]. The similar artificial periodic media were previously investigated in the context of atomic condensates placed in optical lattices which are completely conservative and also in the purely optical dissipative systems. However in our particular case the presence of incoherent reservoir crucially affects system properties. Besides, the exciton-polariton systems possess strong nonlinear properties which should necessary be taken into account under high level of pimping.

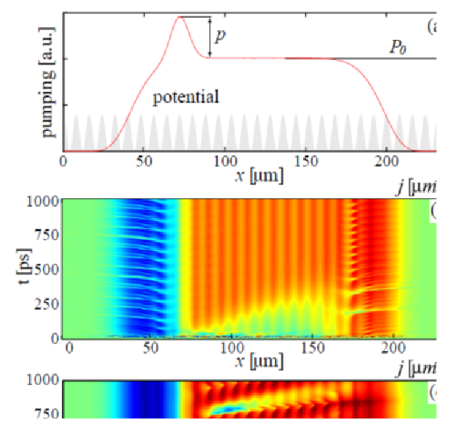

Fig. 1: The suggested scheme of pump allowing for experimental observation of the current states. (b) Laminar dynamics of the coherent polaritons current j for the pump peak amplitude $p = 8\ \mu\mathrm{m}^{-2}\mathrm{ps}^{-1}$ and background pumping rate $P_0 = 50\ \mu\mathrm{m}^{-2}\mathrm{ps}^{-1}$. (c) Turbulent dynamics of the polariton current for $p = 16\ \mu\mathrm{m}^{-2}\mathrm{ps}^{-1}$ and $P_0 = 50\ \mu\mathrm{m}^{-2}\mathrm{ps}^{-1}$.

The condensate dynamics is described within the framework of mean-field theory by the coupled equations for the order parameter and for the density of incoherent polaritons. Firstly, we identify different regimes of both relaxation and oscillatory dynamics governed by superpositions of Bloch eigenstates of coherent exciton polaritons within the periodic lattice. In particular, the robust oscillations between different metastable Bloch states of the periodic condensate band-structure were predicted [3]. An appearance of such oscillation can be explained in terms of the effect of *spatial hole burning* in reservoir distribution which is responsible for spatially distributed gain. The region of existence of such oscillations and their frequency are closely connected with the nonlinear condensate properties and the presence of reservoir.

The influence of the nonlinear exciton-exciton interaction on the system properties were studied in details. It is shown that under certain value of external pump there is a bifurcation of the solution leading to the appearance of a family of essentially nonlinear states. The special feature of these solutions is that its current does not vanish when the quasi-momentum of the state approaches the end of Brillouin zone. Note, that such a current in periodic media is strictly forbidden in the linear case due to Bragg scattering but under strong nonlinearity the periodic potential becomes effectively screened by the nonlinearity. The appearance of such current state is accompanied with the formation of energy-loops both at the center and at the end of Brillouin zone.

An experimental scheme allowing the observation of the discussed nonlinear current states is suggested and studied by numerical simulations – see Fig. 1. In particular, it was shown that in the presence of spatially inhomogeneous pump the formation of stable current in polariton system is possible.

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Permanent Rabi oscillations with Exciton-Polariton Non-equilibrium Condensates

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A physical mechanism which maintaining permanent non-decaying Rabi oscillations in driven-dissipative condensates of exciton-polaritons in semiconductor microcavities was discussed and analyzed in details. The proposed method is based on stimulated scattering of excitons from the incoherent reservoir formed by nonresonant pumping. We demonstrate that appearance of permanent oscillations can be interpreted in the context of the parity-time symmetry in the coupled exciton-photon system. This situation is realized in a specific regime of pumping of the exciton state when pumping dynamically equalizes losses of polariton condensate for both polariton branches.

In particular, we analyze two different mechanisms of pumping of the incoherent reservoir. The first one is based on scattering of reservoir excitons on acoustic phonons. It enables permanent oscillations in the case of balance between gain and losses and under resonant exciton-photon interaction only – see dash-dotted curve in Fig. 1. It was shown that these conditions coincide with parity-time symmetry criteria allowing the real-value eigenfrequencies of the oscillating solution.

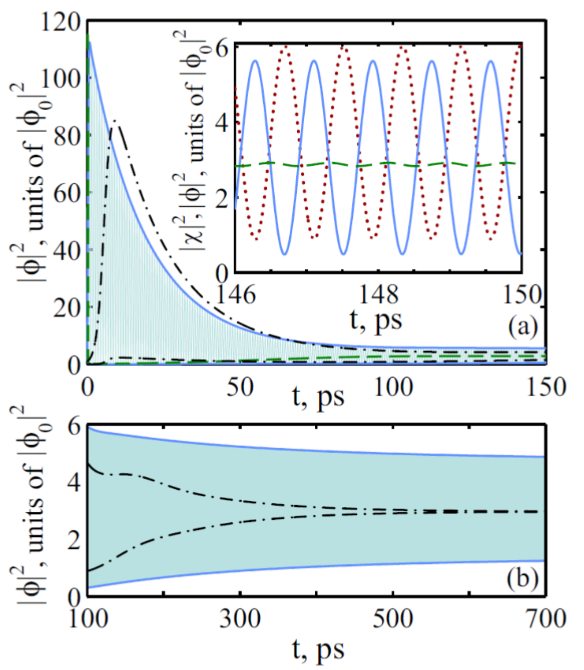

Fig. 1: (a) – Time dependence of photon density $|\phi|^2$ (in the units of initial density $|\phi_0|^2$) in the case of nonresonant exciton-photon interaction. Dash-dotted curve corresponds to the envelope of the oscillation of the photon component in the case of phonon-assisted pumping. In inset the oscillations of photon (dashed) and exciton (dash-dotted) densities are shown on the small short interval. (b) – The same as in panel (a) but for time after $t = 100$ ps.

The second mechanism of condensate pumping is nonlinear and based on the exciton-exciton scattering where excitons possessing momenta $-\mathbf{k}$ and $\mathbf{k}$ scatter into the condensate state with the momentum $\mathbf{k} = 0$. This mechanism turns out to be more flexible and can maintain permanent oscillations in wide range of system parameters including non-zero exciton-photon detuning – solid curve in Fig. 1. In the latter case robust permanent Rabi oscillations occur with unequal amplitudes of exciton and photon components (see inset in Fig. 1). In spite of the fact that the criteria of the PT-symmetry is not fulfilled in the case of such nonlinear pumping, the eigenfrequencies of the system still remain purely real which allows for undumped Rabi oscillations. It means that in this case exciton-polaritons exhibit properties of a pseudo-Hermitian system.

We also took into account experimentally observable additional dumping of upper branch polaritons and energy blue shift of the condensate arising form exciton-exciton interactions. Our analysis shows that the unique nature of the proposed mechanism of pair scattering of reservoir exciton allows for permanent Rabi oscillations in this case as well. Our predictions pave way to realization of integrated circuits based on exciton-polariton Rabi oscillators.

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Magneto-optical light modulator with the domain wall manipulation via flexomagnetoelectric effect

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We proposed a scheme of Faraday magneto-optical light modulator with magnetization control via flexomagnetoelectric effect. Our earlier researches of bismuth-substituted iron garnets films showed the giant domain wall (DW) displacement in electric field of charged tip due to flexomagnetoelectric effect [1, 2]. The displacement of DW may be increased with in-plain magnetic field applied normally to the DWs. Observed displacements in this case are up to half of the domains width (Fig. 1(a,b)). Considering such giant DW displacement we proposed and realized the Faraday magneto-optical light modulator with local magnetization control. The ferromagnetic dielectric film with composition $(BiLu)_3(FeGa)_5O_{12}$ was placed between two electromagnets with fields orientations in plane and normally to the film. Laser beam passes through the polarizer film analyzer and its intensity is detected. Two parts of the laser light pass through two domains with opposite magnetization orientations and obtain opposite polarization rotation due to Faraday effect. DWs displacement changes the ration between the beam parts and the total light intensity passing through the analyzer, as a result. Amplitude and sign of intensity modulation depends on spot size, angle between polarizer and analyzer, relative positions of the light spot, DW and tip. Varying the parameters we experimentally obtained the linear regime with the modulation depth δ = [I(V)-I(0)]/I(0) up to 270%, where V = -1000 V is tip voltage (Fig. 1(c)).

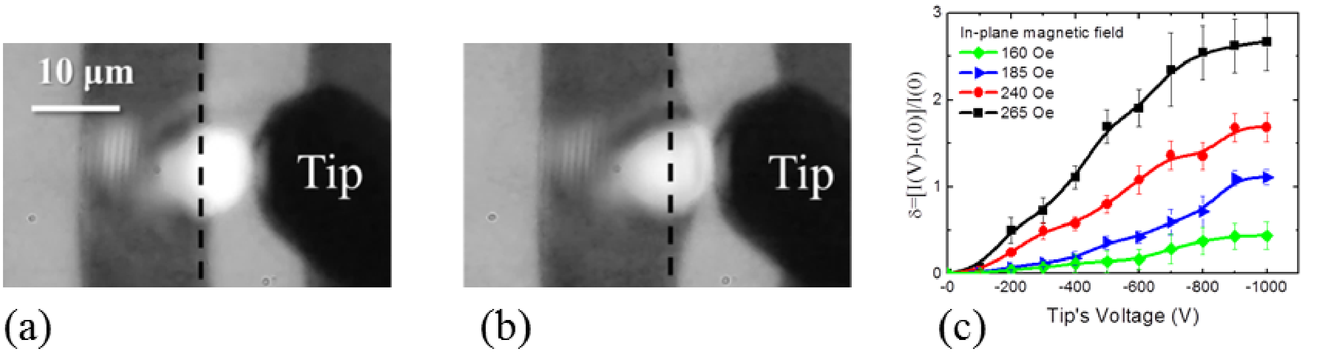

Fig. 1: (a, b) Domain wall displacement due to magneto-electric effect. Tips voltage is (a) 0 V, (b) -1000 V; white spot is laser spot. (c) Lasers intensity modulation via tips voltage.

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Photoemission of electrons from plasmonic nanoantennas

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A boom of interest in the generation of hot photoelectrons in plasmonic nanostructures is occurring at present because electric field enhancement near plasmonic nanoantennas can substantially increase the electron photoemission [1] compared to photoemission from flat metal surface. This effect can be used in optoelectronics (for instance, in order to increase the quantum efficiency of Schottky photodetectors), photochemistry, photoelectrochemistry, as well as in molecular electronics in all areas of science and technology where the generation of hot photoelectrons and their subsequent utilization play a principal role. The goal of our presentation is to give an introduction into the rich physics of photoemission of electrons from metal nanoparticles [2]. In particular, the role of transition absorption (absorption of a photon by an electron passing through an interface of two different media) in the photoeffect will be highlighted [3-4]. Additionally, the giant photogalvanic effect (directionally preferential emission of photoelectrons in noncentrosymmetric plasmonic nanoparticles) recently predicted in [5] will be described. This work of AVU was financially supported in part by the Government of the Russian Federation (Grant 074-U01) through ITMO Visiting Professorship program.

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Transition from collective spontaneous emission to coherent superradiance of atoms placed near plasmonic structure

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Interaction of electromagnetic field of photonic and plasmonic structures with atoms and molecules is the central problem of quantum optics [1], chemistry and biology [3], nanophysics [2] that includes plasmonic nanoprobes and biosensors [4]. Besides perspective applications such problems are interesting from fundamental point of view because many phenomena exhibit new features in nanoscale [4].

In this work we consider the superradiant dynamics of two-level atoms placed near plasmonic nanostructure. Superradiance is collective spontaneous emission. One of the main difficulties for superradiance realization is dipole-dipole interaction between atoms. Using photonic and plasmonic structures lead to high interaction of atoms with electromagnetic field of the structures. This interaction may be much larger than dipole-dipole interaction between atoms that creates appropriate condition for superradiance observation [5, 6, 7].

We show that there is the critical value of quality factor of plasmonic modes which divides two different regimes. When quality factor is higher than the critical value, superradiant burst characterizes by power dependence of delay time on number of atoms. The physical nature of superradiant burst in this case is the interference of Rabi oscillations of atoms interacting with plasmon field. When quality factor of plasmonic mode is lower the than critical value, superradiance is induced by collective spontaneous emission in plasmonic mode. Delay time logarithmically depends on the number of atoms as in the Dicke model.

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Violation of Nonreciprocity Principle in a Planar Optical System

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We have theoretically predicted and experimentally verified a giant violation of the nonreciprocity principle in a planar optical system. This system consists of nanoholes made in optically thick metal nanofilm, created on the surface of a multilayered dielectric metamaterial (photonic crystal) [1]. According to the Lorentz reciprocity theorem [2] the optical system is reciprocal. The absence of possibilities to reverse in time an electromagnetic field passing through a nanoholes is an origin of a giant optical nonreciprocity.

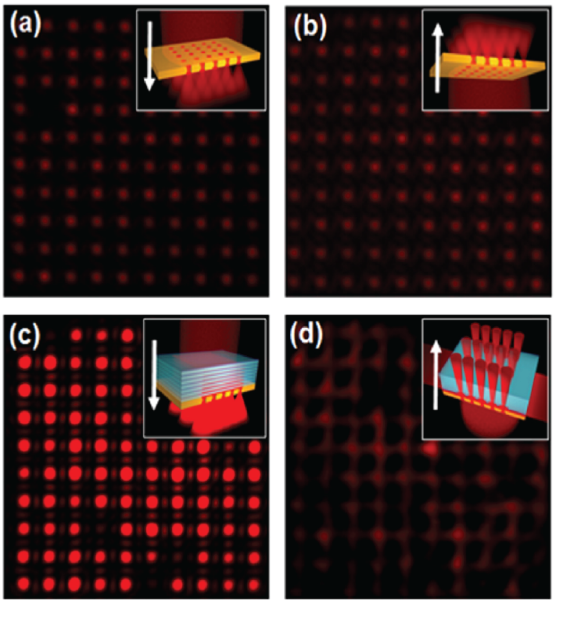

Fig. 1: Experimental realization of an optical nonreciprocity in a planar optical system as well as results of our transmittance measurements in different samples: Au nanofilm with array of nanohes (a,b), Au nanofilm with array of nanohes created on a surface of dielectric metamaterial (c,d). Inserts show direction of incident radiation. As it is seen from the figure, metal nanofilm with array of nanoholes is optically symmetrical while Au nanofilm with array of nanohes created on a surface of dielectric metamaterial is not symmetrical as a result of optical nonreciprocity.

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Hermitian description of localised plasmons in dispersive dissipative subwavelength nanostructures

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The quantum description of an electromagnetic field was developed in 20^{th} Century; nowadays it is the main study approach for the description of numerous physical phenomena. The most convenient way to quantize the electromagnetic field in a vacuum is to use the Coulomb gauge to eliminate the longitudinal component of the electric field. This is possible due to Maxwells first equation in vacuum $\text{div}\mathbf{E} = \Delta U = 0$, and the absence of the canonical conjugate variable to scalar potential U. However, in the medium, the longitudinal electromagnetic field is derived by the equation $\Delta U = -\text{div}\mathbf{P}$, where $\mathbf{P}$ is the total medium polarization, so it cannot be eliminated in the same way as in a vacuum. In macroscopic electromagnetic field quantization, the problem has not been investigated appropriately [1]. The most consistent approach is to quantize the medium polarization and the field simultaneously [2]. This approach demands the choice of a model of the medium. One of the simplest and most usable models for this purpose is the Lorentz model. It assumes that the medium consists of dumped harmonic oscillators. Their relaxation is provided by including additional degrees of freedom (reservoir). The Hamiltonian of the system "field + dipole oscillators + reservoirs" is Hermitian, and its quantization can be performed in the standard way by the introduction of creation and annihilation operators. The eigenmodes of the system are collective oscillations of field and medium and can be determined by the Fano diagonalisation method [3, 2]. First, the described procedure was used for the bulk medium [2], then it was generalised to non-uniform media [3]. To obtain the exact solution in the non-uniform case, it is necessary to use the Green functions formalism. However, it is very difficult to give the physical interpretation of each mode of the system, and to separate the field modes from the system. As a result, this approach cannot be applied to find the number of excited plasmons or the electric near field per plasmon of plasmonic nanoparticle.

The widely used phenomenological approach [4, 5] to plasmon quantization is much simpler but not canonical. It treats the localised plasmons as the harmonic oscillators whose eigenfrequencies are the frequencies of the plasmon resonances, and determines the specific normalised condition for each plasmon mode. Namely, the total electric field energy per plasmon is supposed to be equal to the quantum of the oscillators energy . This condition seems to be reasonable, although it has not been derived from the canonical procedure. Therefore, the phenomenological quantization has some drawbacks. In particular, there is no way to describe the Joule losses consistently. For example, the near electric field per plasmon obtained from this method does not depend on the imaginary part of the permittivity. Therefore, the canonical verification of the phenomenological plasmon quantization method is a current and important problem.

In our work we canonically quantize the plasmons, describing the permittivity through the Lorentz model. It is shown that the electric field per plasmon is fully described by the permittivity defined from the solution for bulk medium. We show that in the low loss limit, the quantum of plasmon electric field has the same value as the quantum obtained from phenomenological theory [4, 5]. Also, we find the correction to the quantity obtained from phenomenological theory. We find in the Coulomb gauge the oscillations of medium subsystem response for quantization of scalar potential, separately we quantize the vector potential corresponding to photon subsystem. These quantum subsystems interact due to excitation of plasmonic resonances in the nanosphere. The excitation of one of the subsystems causes the excitation of the other. This fact, as we show, relates to the retardation character of the electromagnetic field outside the nanosphere. We derive canonically conjugated variable to electric field. Finally, we replace the model permittivity by the real values for gold and silver to obtain the electric near field per plasmon for real materials.

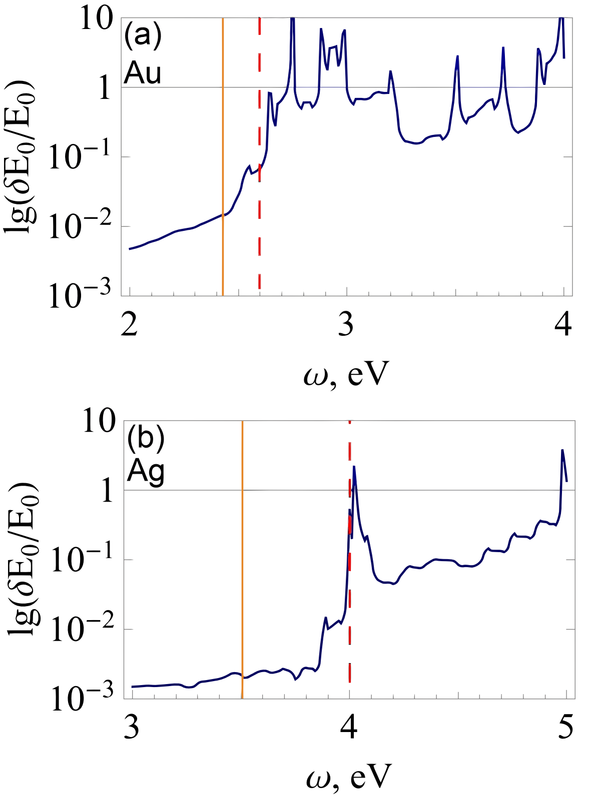

Fig. 1: Correction to the electric near field per plasmon due to the imaginary part of permittivity depending on frequency for (a) gold and (b) silver. The vertical dashed lines mark the interband transition frequency. The vertical solid lines mark the frequency of dipole plasmonic resonance.

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Noise suppression in nanoplasmonic systems

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Stochastic resonance (SR) was discovered relatively recently, at the end of the last century. It became clear that the considering of noise and fluctuations is vital in the vast majority of both applied and theoretical problems. Stochastic resonance [1] is an effect which combines the group of phenomena where the response of a nonlinear system to a weak external signal dramatically rises due to the increase of the noise intensity in the system. Herewith, some integral characteristics of the system output, such as signal/noise ratio, have a distinct maximum at an optimal value of the noise, while the entropy of the system reaches its minimum. The noise in systems appears due to the presence of the dissipation. This fact is the consequence of the fluctuation-dissipation theorem (FDT).

In this paper we consider the evolution of a number of self-oscillating driven systems under the influence of the noise, namely, Van der Pol oscillator and plasmonic nanolaser [2, 3]. It is shown that there is a critical value of the pump, wherein the work of the external force on the system vanishes. SR in this case manifests in the suppression of the noisy part of the systems response. Furthermore, it is observed at the critical value of the pump. Also the result can be achieved using the under threshold pumping. Therefore, we can treat this phenomenon as the inverse FDT, which claims: if there is no dissipation in the system, there is no noise as well. This statement was obtained analytically using Fokker-Planck equation formalism [4]. It is of a general nature and valid for the wide class of non-conservative systems.

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Hybridization of MAB and L-MAB methods

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Properties of metamaterials and plasmonic systems are determined by resonance characteristics of constituent elements. Development of calculation methods preserving both high computational efficiency and accuracy of resonant properties is required. A hybrid technique to calculate metamaterials and plasmonic systems joining possibilities of Method of Minimal Autonomous Blocks (MAB) [1],[2] and Linear Minimal Autonomous Blocks (L-MAB) [3] methods is developed. Method of Linear Minimal Autonomous Blocks (L-MAB) is an extension of MAB method, it provides more accurate calculation of the field distribution in highly inhomogeneous regions due to using additional linear basis functions (E- and H-waves) for approximation of the field in blocks [3]. The developed technique makes it possible to use blocks of different types in different parts of the domain under consideration. Possibilities of the hybrid technique are illustrated at example of numerical solution for problem of plane linearly polarized electromagnetic wave diffraction at periodic grating of perfectly conducting infinitely thin strips. This problem has analytical solution when width of strips d is equal to half of the grating period [4]. Normal incidence is considered. Electric component of the field is parallel to strips. Initial diffraction problem is reduced to a periodic cell split to 20x30 blocks with equal dimensions. L-MAB blocks are used for two rows adjacent to the grating, usual MAB blocks are used as the remaining blocks. Transmission and reflection coefficients are computed in the range of wavelengths by iteration algorithm with account of single-mode approximation of scattering. Dependencies of transmission coefficient absolute values for the plane wave transmission through the on strips wave dimensions derived by the exact model, by MAB method, by L-MAB method and by the hybrid technique are shown in Figure 1.

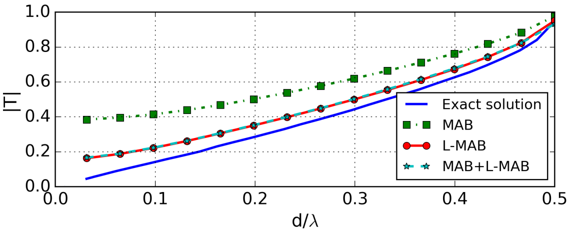

Fig. 1: Transmission coefficient absolute value dependence on strips wave dimensions.

Computation results confirm correctness and efficiency of the proposed hybrid technique.

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The electromagnetic properties of composite materials based on the volume arrays of conducting fibers with dielectric insertions

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Composites and metamaterials are widely used in the optical and microwave techniques. The electromagnetic properties of composites depend on the design and material parameters. Development of effective technologies designing and manufacturing such materials is an important and actual problem.

The object of the study are composite materials, which include: a dielectric matrix, periodic lattice of wire elements and the insertion of arbitrary dielectric materials. The method of minimal autonomous blocks was used to analyze the electromagnetic properties of composites [1, 2] and the methodology for determining the effective electromagnetic parameters based on it [3.4]. The interaction of a plane linearly polarized electromagnetic waves with a flat composite layer was considered as a model problem.

Influence of bulk periodic lattice of conductive wire elements on the spatial distribution of the electromagnetic component in the composites was investigated numerically. In the example of the volume grating of periodic linear conductors a possibility of concentrating the electromagnetic field in the gaps between the ends of neighboring elements it was shown. It is found that the effective electromagnetic properties of such composites strongly depend on the dielectric characteristics of the inserts placed in the gaps between the conductive elements. Effect of composite structures on spatial localization characteristics of an electromagnetic field was investigated.

The possibility of using this effect to create a composite of the following types (radar absorbing materials; nonlinear materials; materials with controlled electromagnetic properties) were investigated.

It offers efficient algorithms for synthesis of composites with desired electromagnetic properties based on a variation of the electromagnetic characteristics of the dielectric inserts.

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The investigation of fluorophosphate glass doped with ZnS optical properties after ion exchange

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Glasses activated semiconductor nanocrystals have interest for study of the fundamental laws due to quantum size effect and for the objects of applied optics. Applied interest in these glasses is associated with their high nonlinearity and the ability to use them as active medium in creating solid state lasers [1, 2], the second harmonic generation [3], as well as memory elements for a new generation of computers [4]. Quantum dots synthesize in silicate glasses by the method of colloid chemistry in liquid medium. We use fluorine phosphate glasses for ZnS- and Ag_2S Quantum dots (QDs) preparation. In our resent works the CdS, CdSe, PbS, PbSe QDs were synthesized in this matrix. Two samples of glass were prepared for the formation of the QD-; glass 1 the host glass doped with ZnS in high concentration and the glass 2-glass 1 after Ag+ -Na+ ion exchange at 320 degrees during 60 minutes. Quantum dots are formed during heat treatment at the temperatures above Tg., It was observed that heat treatment of the glass 1 results in the shift of the absorption band to longer wavelengths (Fig. 1a), which is due to the growth of ZnS quantum dots in the host glass. Absorption spectrum of the glass 2 after ion exchange (Fig. 2) shifts to the NIR spectral region up to 1400nm. QDs formation I is confirmed by the. X-ray diffraction data demonstrate formation phase Ag_2S in the ion exchanged areas of the glass.

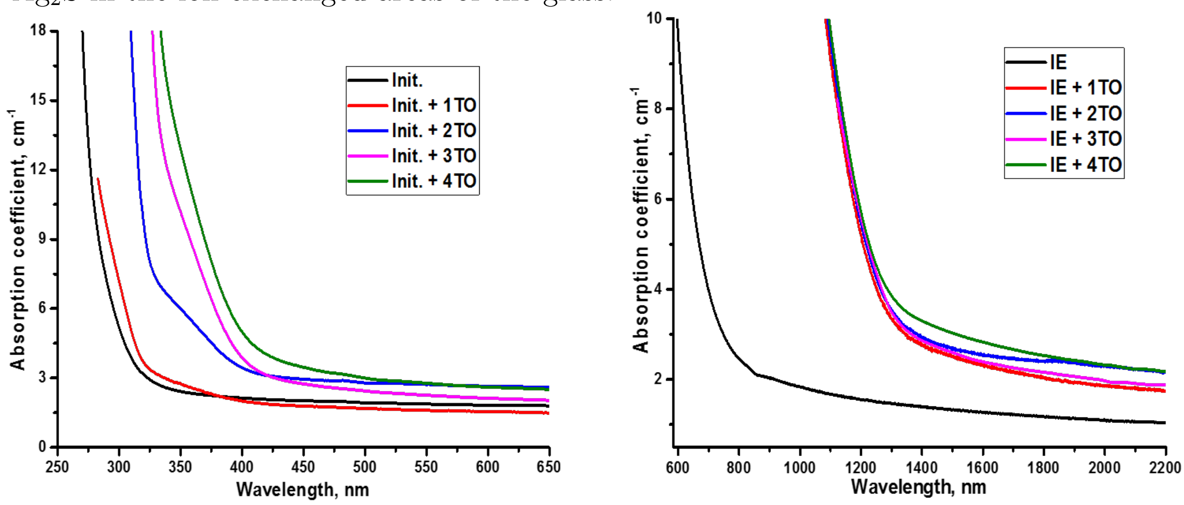

Fig. 1: (left) The absorption spectra of the glass1 and after heat treatments. (right) The absorption spectra of glass2 after heat treatments.

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Two-dimensional cavity magnetoexciton-polaritons

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The energy spectrum of the 2D cavity magnetoexciton-polaritons has been investigated previously, using exact solutions for the Landau quantization of conduction electrons and heavy holes provided by the Rashba method [1]. Two lowest Landau quantization levels for electrons and three lowest Landau levels for heavy-holes, lead to the construction of the six lowest magnetoexciton states. They consist of two dipole-active, two quadrupole-active, and two forbidden quantum transitions from the ground state of the crystal to the magnetoexciton states. The interaction of the four optical-active magnetoexciton states with the cavity mode photons with a given circular polarization and with well-defined incidence direction leads to the creation of five magnetoexciton-polariton branches. The fifth order dispersion equation is examined by using numerical calculations and the second order dispersion equation is solved analytically, taking into account only one dipole-active magnetoexciton state. The effective polariton mass (left) on the lower polariton branch, the Rabi frequency and the corresponding Hopfield coefficients (right) are determined in dependence on the magnetic field strength, the Rashba spin-orbit coupling parameters and the electron and hole g-factors [2].

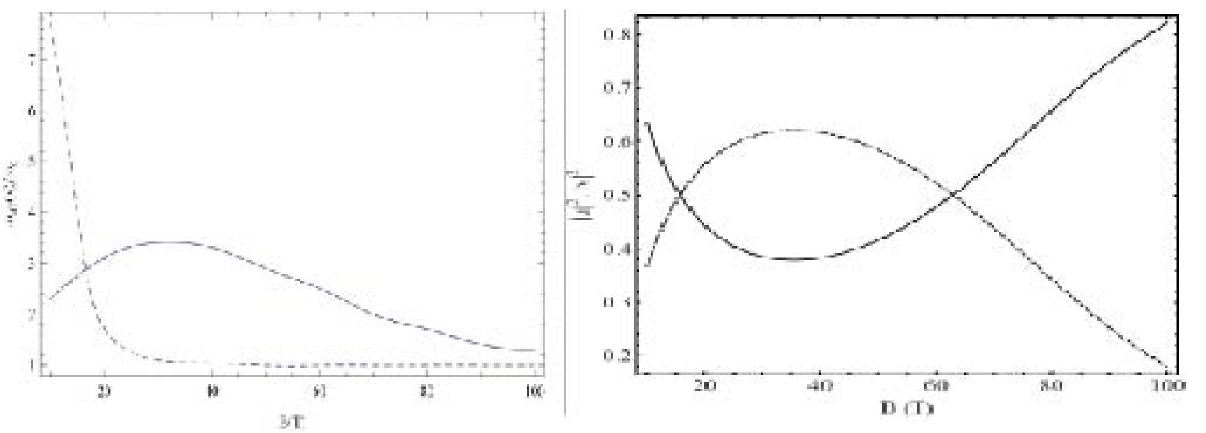

Figure 1: (left) The dimensionless effective polariton mass $m_{eff}(0)/m_C$ in the point $k = 0$ of the lower polariton branches in dependence on the magnetic field strength B in the presence (solid line) and in the absence (dashed line) of the Rashba spin-orbit coupling. (right) he dependences on the magnetic field strength B of the Hopfield coefficients square moduli $|u|^2$ (solid line) and $|v|^2$ (dashed line) in the case of magnetoexciton state F_1 interacting with the cavity photons in the presence of the Rashba spin-orbit coupling.

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Ab initio calculation of the complex dielectric function of cobalt octaethylporphyrin by the projector-augmented-wave method and GW approximation

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We present in this work a study of the complex dielectric function of the cobalt octaethylporphyrin (CoOEP) in the framework of first-principles calculations with G0W0 approximation. The calculation of the complex dielectric function proceeds in two steps: First, we use density-functional theory within the generalized gradient approximation (GGA) to obtain the structural and ground-state electronic properties of CoOEP. Second, the quasiparticle band structure is calculated within GW approximation for complex dielectric function. The key ingredient of GW approximation is electronic screening. We incorporate it into the standard non-self-consistent G0W0 approximation [1], using implementation in Vienna ab initio simulation package (VASP) [2] from the convolution of the single-particle propagator G0 and the dynamically screened Coulomb interaction W0 in the random-phase approximation (RPA) and the time-dependent (TD) DFT approximation. We had some of the difficulties by applying the GW approximation to large molecule of CoOEP. So far, reliable calculations of complex dielectric function within the GW approximation have been done for confined system with up to a few tens of atoms [3,4,5,6,7]. The GW approximation for molecules is implemented by placing them in a large supercell [5]. This is a perfectly justifiable procedure, but it increases the computational effort when supercells are required to be large. The calculated frequency-dependent complex dielectric function of the CoOEP are characterized by peak in the imaginary part originating from interband transition. We conclude that the TD DFT and RPA approximations agree in the peak of the complex dielectric function

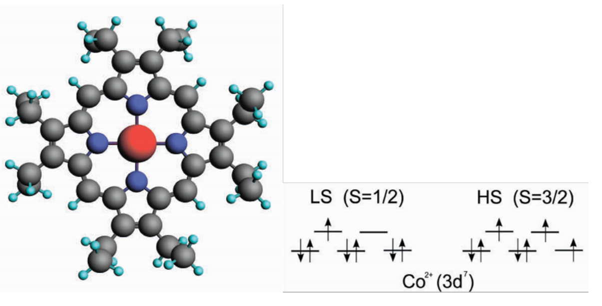

Fig. 1: (left) The molecular structure of CoOEP; (right) Two possible electron configuration of cobalt in CoOEP.

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Fabrication of diffraction gratings and 2D photonic crystals in a Si on insulator waveguide by plasma and wet etching of Si

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The integration of micro and nanophotonic devices on the traditional CMOS platform holds promises for overcoming the limitations of traditional silicon electronics. It is well known that employing waveguide configurations would open up wider potentialities of optical integration and its compatibility with CMOS processing techniques [1].

In the currently presented report a fabrication process is described including electron beam (EB) lithography, plasma and wet etching of Si for polycrystalline Si strip–like waveguides, waveguide lamellar diffraction grating and 2D photonic crystal structures tuned to an electromagnetic wave with the wavelength 1.5 μm. The SiO_2 layer is produced by dry oxidation of the Si wafer. A polycrystalline Si layer was deposited by EB evaporation of a Si target. Strip–like waveguides are fabricated on the basis of $Si/SiO_2/Si$ or SiO_2/Si substrates. The waveguide lamellar diffraction gratings have grooves with a thickness from 40 to 265 nm and the pitch from 340 to 600 nm. The photonic crystals are composed of either Si pillars or cylindrical pores in the Si waveguide which is situated on the surface of a SiO_2 (1 μm thick)/Si–wafer substrate.

The measured attenuation coefficient of the polycrystalline Si waveguide is estimated to be 0.17 dB/mm at a wavelength of 1.5 μm.

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Thin film generator of surface plasmon polariton pulses

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Physical model of compact generator based on plasmon waveguides to produce short optical pulses with a controllable terahertz repetition rate is proposed. The pulse generation is produced by modulation instability of surface plasmon polaritons (SPPs) in a structure with a silver film of subwavelength thickness.

It is shown that during a time interval of a few picoseconds the slightly modulated SPP wave is transformed into a train of pulses due to nonlinear effects. In the case of the film thickness of 5 nm, the pulsation frequency equals 4.6 THz, the duration of each pulse is less than 0.1 ps. For the film thickness of 10 nm (Fig. 1) the temporal dynamics at any given point looks like separated pulses of longer duration 0.5 ps attributed to a smaller group velocity of SPP. In this case the repetition rate of the pulse train is about 1.4 THz. In both cases the peak intensity is about 6 times higher than the intensity of the original SPP wave.

The evolution of the modulated SPP wave is cyclical: the initial wave is transformed into a train of pulses that then transforms into a modulated wave to be decomposed into a sequence of pulses again, and so on. The period of the cycle depends on the relation between the dispersion and nonlinearity coefficient of system under consideration. For the used system parameters, the period of SPP wave evolution is few picoseconds. The SPPs of the required intensity and spatial period of modulation could be generated by using commercially available laser sources of moderate power.

This work was supported by the Ministry of Education and Science of the Russian Federation (Project 14.Z50.31.0015, State Contract 3.2202.2014/K) and The Russian Foundation for Basic Research (Project 15-07-08111).

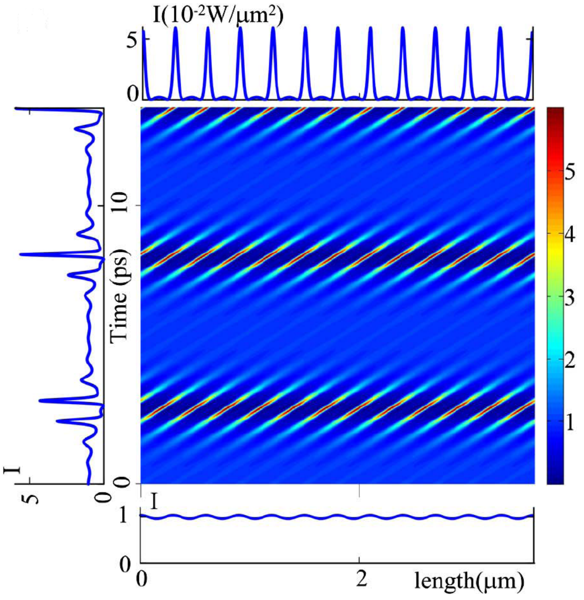

Fig. 1: Evolution of the SPP intensity in the film of thickness 5 nm; the initial wave (at t=0), modulated along x-coordinate (in bottom); time dynamics of the wave intensity at x=0 (left); spatial distribution of the SPP intensity (top) at t=16 ps.

Resonant energy transfer in epitaxial CdSe quantum dots

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Epitaxial CdSe/ZnSe II-VI quantum dots (QDs), have great potential for nanolaser application. One of their main features is a relatively narrow width of photoluminescence (PL) band (40-50 meV) that contradicts the broad distribution of sizes in inhomogeneous QD arrays with high lateral densities ($>10^{1\ 0}$ cm^{-2}), revealed by transmission electron microscopy (TEM) studies. The latter give us not only the size statistics, but also exhibits the spatial arrangement of subsystems of the small and large QDs. These data, along with narrow exciton lines of single QDs recorded by micro-PL spectroscopy instead of a smooth band, i.e. the spectral selection of a limited number of radiating QDs [1], are suggestive of effective Förster resonance energy transfer (FRET) in such QD arrays. Comprehensive

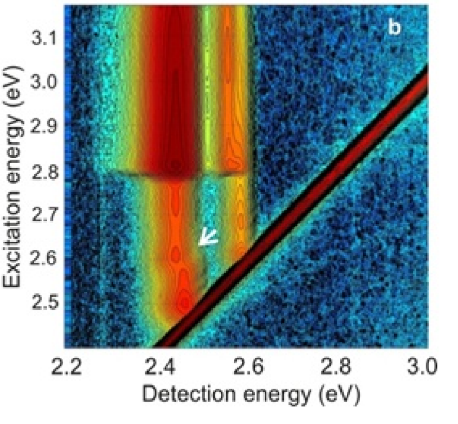

Figure 1: Hyper PL excitation spectrum measured in structure with two insertions of CdSe QDs at 10 K, where the colour represents PL intensity (decreasing from red to blue) in logarithmic scale.

studies of structures fabricated by molecular beam epitaxy, which contain CdSe fractional monolayer insertions into a ZnSe matrix, demonstrate that in these arrays the exitonic FRET between ground and excited levels of small and large QDs, respectively, controls PL characteristics when the excitation is below ZnSe barrier energy. With this mechanism, the small QDs play a role of “donors” providing effective carriers trapping and fast excitation transfer towards “acceptors” (faster than the recombination of the donor-QDs themselves).
Theoretical modeling, which considers the QDs as spheroids with a Gaussian potential profile [2], shows that, in general, the architecture of quantum levels can promote two types of FRET. The first one involves the excited excitonic states, while the other can take place between the ground states of neighbouring QDs, which have close energies. We demonstrate for the first time an abrupt switch between these two mechanisms. In hyper PL excitation spectra, it gives rise to a strong blue shift of PL (about 25 meV) at the energy of 2.55-2.6 eV predicted by the modelling. This feature is observed in structures with both single and double insertions, when the latter are separated by a barrier of a variable width to control the FRET efficiency. Our data show that the FRET can enhance emission of selected radiating QDs in nanolasers.
Acknowledgment : These studies are supported by RSF (Project #14-22-00107).

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Amplification of the THz oscillations and lasing effect in asymmetrical graphene-semiconductor hyperbolic metamaterial

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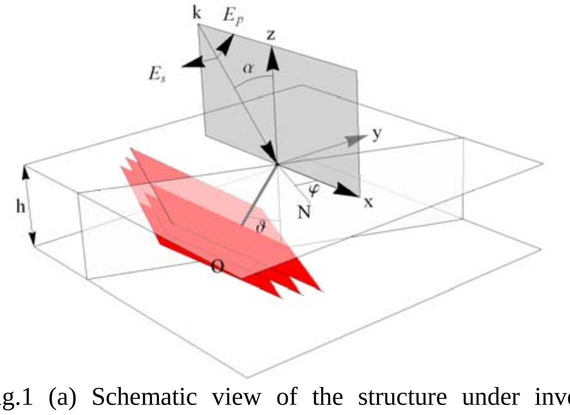
We investigated nanosize asymmetric hyperbolic metamaterial (AHMM) contains graphene and semiconductor (silicon carbide) layers titled according to outer boundary. Early we have shown a broad-band total absorption of radiation in optical region of frequencies and a strong gain in THz region [1,2] for similar kind of AHNN based on graphene and non-active dielecrtic. Here we investigate SiC-graphene structure which is promising due to realistic technology condition for its manufacturing. Amplification of the THz oscillations and lasing effect in such structure will be present in this work. Effective susceptibility of the medium is calculated showing the gain in THz frequency range depending on the graphene chemical potential. We took in to account dynamic characteristics AHMM: conductivity of graphene and total permittivity of the structure.
We have used an algorithm for solving of the Maxwell equation using the Berreman 4x4 matrix which is convenient for the investigation of the propagation of polarized light in anisotropic media. We have adopted this method for the calculations of light propagation in AHMM slabs which is infinite in the x and y-direction and has a finite-thickness in the z direction. The optical axis orientation is given by Euler angles and incidence angle and perpendicular to the graphene sheets (fig.1a).



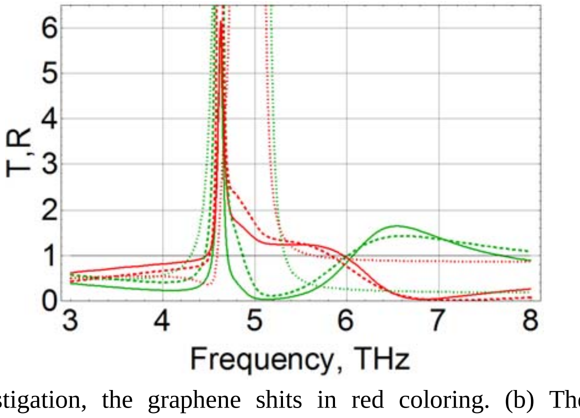


Fig.1 (a) Schematic view of the structure under investigation, the graphene shits in red coloring. (b) The transmission (green curves) and reflection (red curves) coefficients vs frequencies: h=3, θ=π/3.8, T=300ºK, φ=π/2; α=π/4 (solid lines), α=π/3 (dashed lines) and α=π/2 (dotted lines).

Here we use the effective medium model (Maxwell–Garnett homogenization) which was verified comparing with the more accurate analyzing the periodic graphene lattice in our previous work. The transmittance and reflectance were calculated for different orientation of optical axis, angles of incidence α and THz field frequencies. We present dependences transmission and reflection coefficients vs frequency for different angles of incidence α (Fig.1b) and vs incident angle for different parameters of the AHMM. The affects of changing of the parameters of structure has been estimated. High gain in the medium considered is predicted numerically. Threshold condition for THz oscillations in the SiC-graphene slab structure with hyperbolic dispersion is formulated by aforementioned method. The procedure for calculations of the threshold condition for THz oscillations is present for this and similar structures. The gain saturation effect and electric field distribution in SiC-graphene AHMM will be present.

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Self-consistent Purcell factor and spontaneous topological transition in hyperbolic metamaterials

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The Purcell factor for finite-size dipole placed in hyperbolic metamaterial has been already studied in Ref.[1] and this theoretical model consider weak-coupling regime. However, hyperbolic metamaterial is higly dispersive media and we suppose that frequency dispersion of effective parameters of metamaterial should be taken into account. So in this work we calculates Purcell factor considering dispersion (we call this case "self-consistent") and also theoretically predict the possibility of spontaneous topological transition arising from huge Purcell factor in such system.

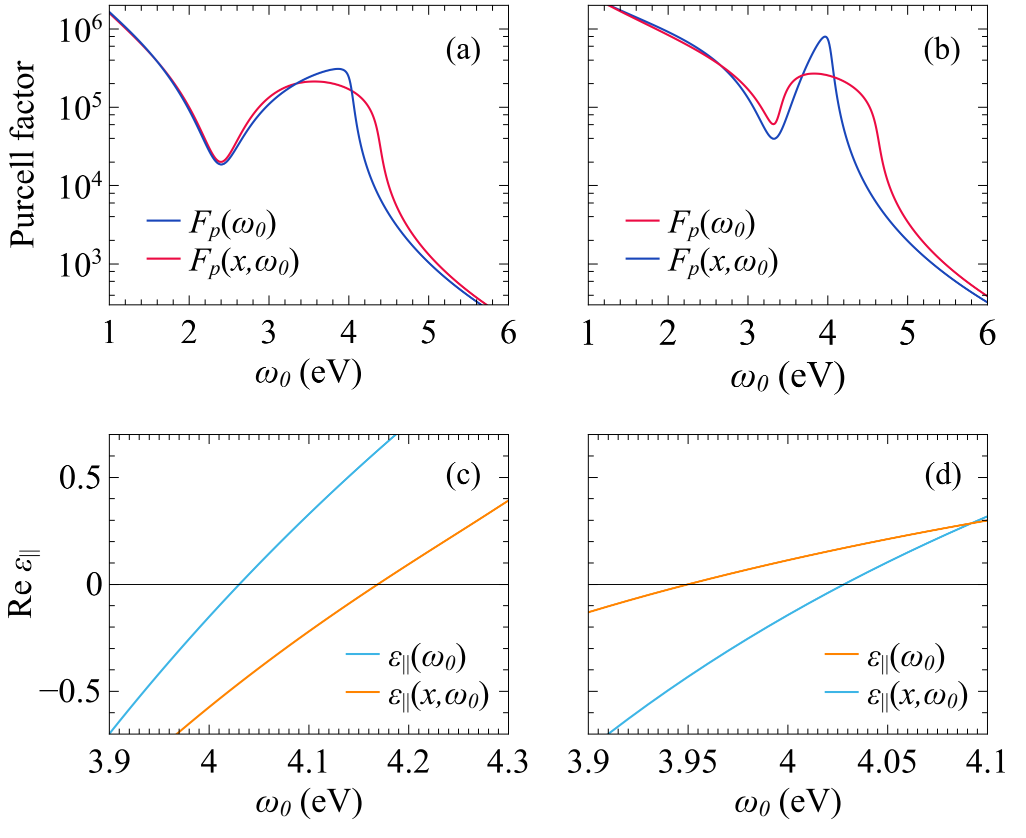

Fig. 1: (a,b) Purcell factor calculated within weak-coupling model (red line) and within self-consistent model (blue line). (c,d) Real part of parallel component of effective electric tensor. Orange line corresponds to self-consistent case and light-blue – to weak-coupling case. There is spontaneous topological transition (c) from hyperbolic regime (with $\varepsilon_{\parallel} < 0, \varepsilon_{\perp} > 0$) to elliptical regime ($\varepsilon_{\parallel} > 0, \varepsilon_{\perp} > 0$), and (d) from elliptycal regime to hyperbolic one. The size of the dipole is 2.2 nm. Hyperbolic metamaterial is layered structure with gold metal layers and dielectric layers with permittivity (a,c) $\varepsilon_d = 9$, (b,d) $\varepsilon_d = 2.2$.

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Garnet-based magnetoplasmonic sensor with ultra-high SPR quality factor

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We present a novel plasmonic magnetophotonic sensing heterostructure with ultra-high quality factor surface plasmon resonance (SPR). Nowadays SPR sensors are one of the most precious ones and their further development is perspective for a wide range of applications in various fields including biological, medical and chemical investigations [?]. One of the most pronounced problem of the such sensors is rather large width of SPR caused by inclusion of lossy metals in the structure. The quality factor of the resonance can be increased by the utilization of the long-range propagating modes in symmetrically surrounded plasmonic films or photonic crystal-based heterostructures with specially tuned layer impedance. Another way of SPR sensor improvement is measurement of the magnetooptical spectra, spectra of transverse magnetooptical Kerr effect (TMOKE), namely, instead of reflection one since the magnetooptical resonance is sharper [?, ?]. The reported magnetoplasmonic sensors were based on ferromagnetic metals with intrinsically high losses that broadened the SPR resonance.

We propose to include bismuth-substituted iron garnet in the plasmonic heterostructure since on the one hand, it allows for the observation of the magnetooptical effects, and, on the other hand, possess low losses compared to ferromagnetic metals. At the same time photonic crystal is included in the plasmonic structure in order to excite the long-range propagating mode in thin gold film surrounded by garnet with very high refractive index ($n \approx 2.2$) on the one side and analyzed gas with very low refractive index ($n \approx 1$) on the other side.

The fabricated sample consist of SiO2/Ta2O5 photonic crystal covered with 90 nm bismuth garnet film and 8 nm gold layer. The sample was designed to show the ultra-narrow SPR and TMOKE resonance at the operating wavelength of 790 nm. The width of the TMOKE resonance is measured to be 0.06° and the width of SPR is 0.1°. Under the variation of the refractive index of the analyte gas the position of the SPR and TMOKE resonance experience shift equal to 46°/RIU (refractive index unit). Due to the resonance narrowness the sensitivity of the reflection coefficient to the environmental refractive index change was measured to be $2.6 \cdot 10^4$%/RIU and the sensitivity of the TMOKE resonance is $1.8 \cdot 10^3$%/RIU. The fabricated heterostructure was tested to work as gas sensor while the gas cell was filled with air or helium.

The work was supported by Russian Science Foundation (grant 14-32-00010).

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REFRACTION ANGLE OF ELECTROMAGNETIC WAVE ON A WIRED STRUCTURE PRISM

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In this work, we considered wired structure as an effective medium that can be described by electromagnetic properties μeff, εeff и neff. The samples under investigation were dielectric prisms consisting of periodically arranged with the lattice constant a=7mm conductive wires. It was obtained in [1] that given medium has neff~1 at frequency 12 GHz.
According to this, we fabricated and investigated samples with various angles of the facet of the prism (fig. 1a) to prove that specified wired structure is an effective medium at frequency 12 GHz and electromagnetic wave passes without deviation for various angles. All the measurements were performed on the angular spectrometer (fig. 1b) described in details in [1].
The results of refraction dependencies on the angle are shown on the fig. 2.

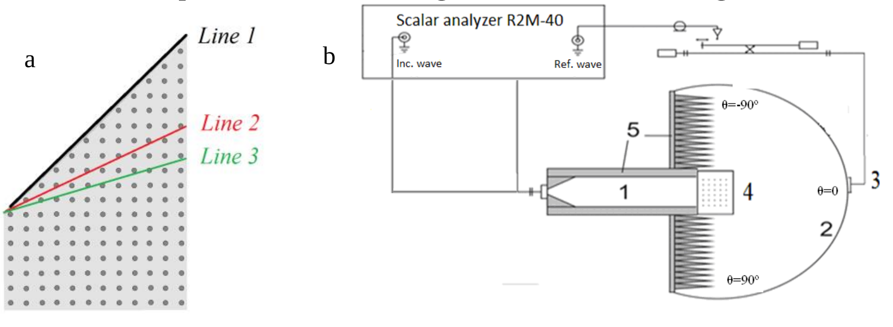

Figure 1. Fabricated prisms with several angles of facet (a): Line 1 – 45°; Line 2 - 26° ; Line 3 - 14. Experimental setup (b).

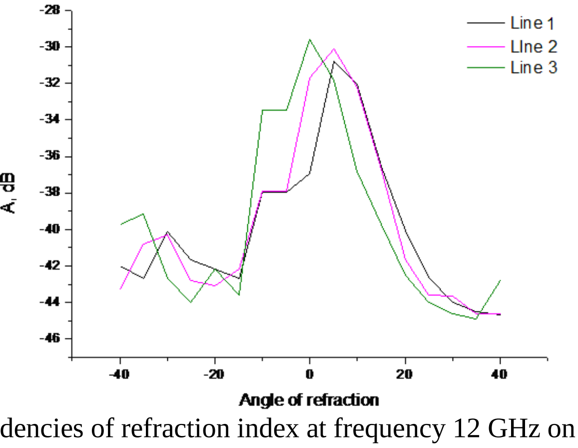

Figure 2. Angular dependencies of refraction index at frequency 12 GHz on the prisms with various angles of the facet.

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Magneto-plasmonic effects in graphene-covered gyrotropic nanowires

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External magnetic field can rotate spatially inhomogeneous intensity distribution in cross-section plane of optical fiber [1]. The nature of this effect is magnetic field induced non-reciprocity in propagation of the modes rotating in opposite azimuthal directions. Recently, we have shown that such rotation may be tuned by chemical potential of graphene in graphene-coated optical fiber, but observable rotation mainfests itself at few centimeters scale [2]. A general trend of increase of magnetooptical effects in magnetoplasmonic nanostructures makes one hope that the abovementioned rotation may be significantly increased in graphene-coated gyrotropic nanowires. We theoretically investigate the Faraday rotation for SPPs propagating on graphene-based cylindrical waveguide filled by magneto-optically active material. Upon the reversal of the external magnetic field some high-order plasmonic modes may be rotated by up to 100 degrees on scale of about 500 nm at mid-infrared frequencies. Tuning carrier concentration in graphene allows for controlling SPP-properties and notably the rotation angle of high-order azimuthal modes.

This work was supporteb by RFBR (♯♯ 16-37-00023, 16-07-00751) and RScF (♯ 14-22-00279).

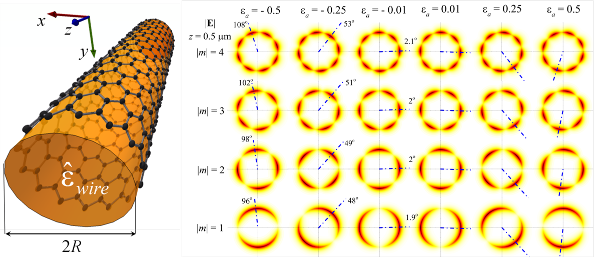

Fig. 1: Geometry of the problem (left) and results of calculations of field distribution at vacuum wavelength 3 μm, core radius 100 nm and different girotropy values (right). First four modes are shown.

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Fundamental transverse plasmonic mode of graphene cylinders

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Transverse surface plasmons (TSPs), i.e. transverse coupled charge-electromagnetic oscillations propagating along conductive surfaces, are very unusual for conventional plasmonics. Graphene proposes a unique possibility to observe these plasmons [1, 2]. TSPs speed is usually close to bulk light one due to transverse motion of carriers. In this work we discuss conditions of TSPs propagation in cylindrical graphene-based waveguides. In contrast to single layer of graphene, negativity of graphene conductivitys imaginary part is not a sufficient condition for TSPs propagation in graphene cylinders. The structure supports TSPs when the core radius of waveguide is larger than the critical value R_{cr}. Critical radius depends on the light frequency and the difference of permittivities inside and outside the cylinder. Minimum value of R_{cr} is comparable with the wavelength of bulk wave and corresponds to interband carriers transition in graphene. We predict that use of multilayer graphene will lead to decrease of critical radius. TSPs speed may differ more significantly from bulk light one in case of epsilon-near-zero core and shell of the cylinder. Some results are shown in Figure 1.

The work performed in part under financial support of Russian Science Foundation (grant ♯ 14-22-00279) and Russian Foundation for Basic Researches (grants ♯♯ 16-37-00023, 16-07-00751).

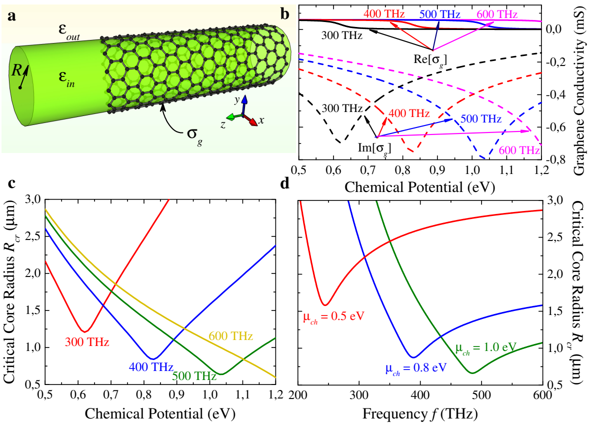

Fig. 1: Geometry of the problem (a), conductivity of graphene versus it's chemical potential at different frequencies (b), critical core radius versus graphene chemical potential (c) and frequency (d).

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Radia and Conductivity dependencies of permeability of mettalized particles

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In this work, we simulated dielectric nonmagnetic and magnetic spherical particles covered by metallic layer. We obtained dependencies of real and imaginary parts of the effective permeability of powders formed by metallized dielectric particles on radia of the dielectric internal core and conductivity of the metallic external shell. We used finite element method for calculation of the electromagnetic fields in the investigated model and combination of impedance lows for perfect electric conductor (PEC) and perfect magnetic conductor (PMC) to calculate effective electrodynamics parameters. Calculation results were compared with previous results obtained in a quasi-stationary approximation and non-directly with experimental data. The imaginary part of the effective permeability is large enough compared with imaginary part of the effective permittivity and reaches its maximum values at the thickness of the metallic layer less than the skin depth. According to simulation results in Fig. 1, we can see that at decreasing the radia of the internal dielectric core the maximum of the frequency dependence of the imaginary part of permeability undergoes the right shift. In terms of microwave sintering, this corresponds as well as decreasing distance between the particles, to the increasing the volume fraction of conductive component in the powder. The nature of this maximum can be explained by the formation of the plasmon on the surface of the conductive shell. One can see in Fig. 1, this type of losses is determined by the conductivity of the shell so that for low conductivities this effect is not observed.

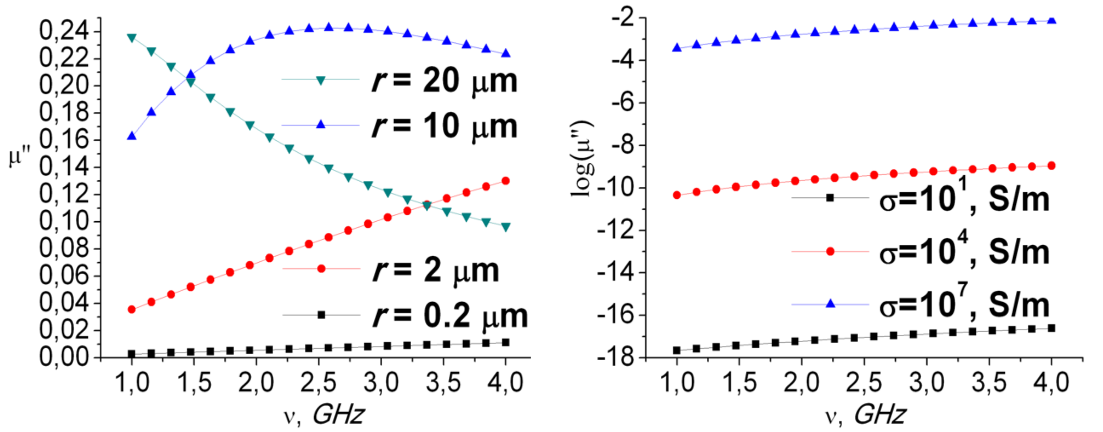

Fig. 1: Dependency of the imaginary part of the dynamic effective permeability of the dielectric-coated conductor particles on the radia of the dielectric core (left) and conductivity of the shell (right). The radia of the dielectric core in the right picture is $r = 10\mu\text{m}$. The conductivity in the left picture is $\sigma = 5,8e^7\text{S/m}$. The thickness of the shell in both is $l = 0.2\mu\text{m}$

Influence of fs-laser melting on the optical properties of hybrid dimer nanoantennas

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Hybrid nanophotonics based on metal-dielectric nanostructures unifies the advantages of plasmonics and all-dielectric nanophotonics providing strong localization of light, magnetic optical response and specifically designed scattering properties. Recently, we have demonstrated a novel type of hybrid nanostructures fabricated by femtosecond laser reshaping of ordered arrays of metal-dielectric (Au/Si) nanoparticles created by lithographical methods[1]. Local laser heating of individual hybrid nanoparticles is applied for selective reshaping of the metal components without affecting dielectric ones, thus engineering both electric and magnetic optical resonances of the nanoparticle. The laser reshaping of gold component in a Au/Si nanoparticle allows to modify optical properties of the nanodimer. To understand the coupling effects in hybrid nanostructures under different degree of fs-laser reshaping, we have performed numerical simulation of hybrid nanostructures pairs. We have investigated scattering spectra and local field distribution of nanoparticles.

Thus, this work represents a next step in understanding of interaction among hybrid nanoparticles in array. The results of the work can be applied in optical properties engineering of metasurfaces for perspective nanophotonic devices.

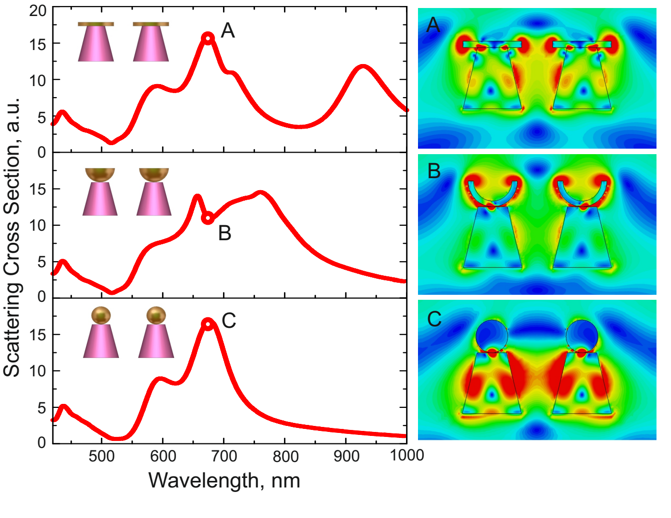

Fig. 1: Numerical modeling of scattering spectra of hybrid dimer nanoantennas with different value of fs-laser reshaping. On the right, the distributions of local E-field for wavelength of 670 nm.

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Separation of electric and magnetic field in silicon structure at nanoscale

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Direct and selective excitation of magnetic dipole transitions of rare earth ions and study of similar magnetic aspects of light-matter interactions in optics are of high interest last decades [1]. For these applications it is very important to obtain so-called pure magnetic hot spots where magnetic field is enhanced simultaneously with electric field decreasing down to zero in magnitude. Separation of electric and magnetic fields with reducing of electric component down to zero and enhancement of magnetic component is one of the goals of modern nanophotonics. Here we propose new method to obtain strong separation of magnetic and electric fields in the silicon structure under the plane wave excitation.

Last decades magnetic properties of high-index nanostructures in optics have been studying actively due to discovery of so-called Mie resonances and their wide practical prospects [2, 3]. It has been shown that special configurations of displacement currents in high-index nanoparticles could provide multipoles response what leads to pronounced peculiarities in the scattering and extinction spectra [4]. Due to sensitivity of Mie resonances on the geometrical parameters [5], high-index nanostructures could provide such incredible far-field effects like negative refraction, scattering suppression on the so-called anapole mode and so on. Herewith near-field effects like magnetic field concentration have been considered in the only few papers.

Here we show that in the center of coaxial silicon structure under plane wave irradiation pure magnetic hot-spot can be obtained. Optimization of structure to obtain maximal coefficient of fields separation is presented. Role of multipole interference influence on the effect of separation is discussed.

This method to obtain pure magnetic hot spots seems to be more preferable in comparison with the conventional methods of fields separation like azimuthally polarized beams, nanovortices and so on, due to their universality and simplicity. Thus, in the proposed dielectric structure under plane wave excitation pure magnetic hot spots can be enhanced in the specified position of the structure. This method is prevented from the difficulties of focusing and tuning of lasers beams and complex design of nanovortices and it is suitable for all visible and infrared spectral range.

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High optical gain in phosphorus free 1550 nm laser diodes

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Semiconductor laser diodes with emission wavelength 1550 nm are widely used in digital telecommunication systems [1] and well-studied [2-4]. To satisfy requirements of microwave photonics it is necessary to develop heterostructures with increased frequency of direct current modulation [5]. In this paper we report on optical properties of the strained InGaAs/InGaAlAs/InP heterostructures for active region of laser diode with emission wavelength 1520-1580 nm fabricated by molecular beam epitaxy. Optical properties of the strained heterostructures were investigated by method of photoluminescense. Maximum mismatch parameter between crystal lattice of InGaAs quantum well and crystal lattice of InP substrate as 2% was demonstrated. Utilizing such highly strained heterostructures should increase differential gain of laser diodes [6]. Laser diodes with various cavity lengths, with a stripe width of 60 mm and small mesa were fabricated from the heterostructures. The laser diodes made from the strained heterostructures have five and eight quantum wells as active region. Both type of lasers have shown stable lasing in spectral range 1560-1580 nm. The minimum threshold current density was 1660 A/cm^2 for 2 mm cavity laser, the maximum modal optical gain was more than 175 cm^{-1} and the minimum transparence current was 46 A/cm^2 per one quantum well.

This work was supported by the Ministry of Education and Science of the Russian Federation in the framework of the Federal Target Program “Research and development on priority directions of scientific-technological complex of Russia for 2014-2020”, the code 2015-14-582-0038, agreement 14.581.21.0013, unique ID RFMEFI58115X0013.

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Femtosecond laser ablation for fabrication of gold-silicon core-shell nanoparticles

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Plasmonic nanoparticles have wide range of applications, including optics and biomedicine[1], due to their ability to enhance field. However, metallic particles have some limitations related to high dissipative losses and presence of only electric resonances in simple shape structures (spheres, rods *etc.*). On the other hand, dielectric nanoparticles of high refractive index and low extinction coefficient maintain a strong electric and magnetic resonances in the visible range[2]. In comparison with the plasmonic particles, dielectric have low-losses and can be used for superdirective scattering[3]. Our goal is to combine benefits from both types of nanoantennas.

Recently, it has been demonstrated that spherical high-index crystalline silicon nanoresonators can be fabricated by femtosecond laser ablation of amorphous films[4]. Here we are applying this technique to create core-shell structures from thin gold and silicon films. Resonant core-shell properties depend on the size of the nanostructure. This size can be precisely controlled via thickness of Au/Si films layers.

A strong advantage of our method is that femtosecond laser-induced printing makes possible to obtain nanoparticles with plethora of sizes. Numerical calculations showed the influence of the size of the core and the shell on the optical properties of the particles. These results are in good agreement with series of experimental dark-field scattering spectra. The ability to tune resonances provides the opportunity to use core-shell as a platform for biosensing, directional nanolasers and other applications.

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Fabrication and optical studies of two-dimensional photonic structures

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At the present day the fabrication and investigation of photonic structures are in a high priority. There are a lot of different technologies for photonic structures fabrication at the moment. In the current study we use direct laser writing method. Direct laser writing is a modern technology, which makes it possible to fabricate submicron structures with an arbitrary spatial distribution of material [1, 2]. This method is based on the two-photons absorption effect taking place in a small volume of focused laser beam, where the power density exceeds its threshold value. We could design one-dimensional, two-dimensional, and three-dimensional structures with different shapes and sizes (from hundreds of nanometers to millimeters) by the laser beam focus scanning on photoresistive material [3, 4].

To fabricate two-dimensional photonic structures we use commercially available lithograph (Laser Zentrum Hannover, Germany) and a femtosecond laser (50 fs TiF-100 F) with beam centered at around 780nm wavelength, impulse duration 50 fs and repetition frequency 80 MHz. As polymer material of the structures we choose zirconium propoxide with an Irgacure 369 photoinitiator. Structures with different lattice symmetry, including hexagonal graphene symmetry, is fabricated. Correspondence between mathematical models defined by the path of laser beam and fabricated structures form is confirmed by the scanning electron microscopy.

We studied optical diffraction on fabricated structures experimentally by laser illumination with wavelength $\lambda = 0.53 \mu$m. Diffraction patterns, achieved from samples with graphene-like symmetry have hexagonal symmetry C_6 and consist of intersecting straight lines and hyperboles. The number of lines and hyperbole is a multiple of six. Also we observe a superstructure on diffraction patterns, i.e., straight lines and hyperboles have minima separated by maxima. Obtained results is compared with theoretical diffraction patterns calculated within the Born approximation.

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Chiral near-field formation with all-dielectric nanoantennas

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Nanophotonics has paved the way towards unprecedented level of an optical near-field manipulation at the nanoscale by means of plasmonic and rarer dielectric resonant nanostructures [1]. This became possible after the emergence of optical antennas (or nanoantennas). Currently, nanoantennas have been used to control the local density of optical states, for single nanocrystal and molecule excitation, precise positioning at the nanoscale [2], controlling the scattering directivity, and for the efficient generation of higher optical harmonics [3]. Recently, study of nanoantennas for formation of chiral distributions of the near-field has gained considerable interest.

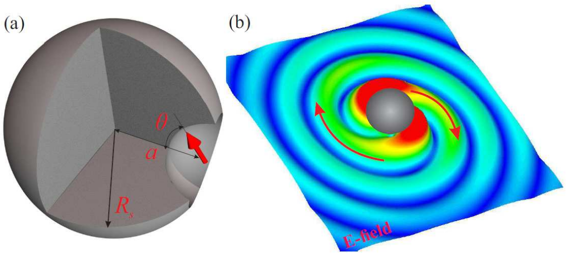

Fig. 1:(a) General view of the considered all-dielectric nanoantenna and orientation of the dipole source (red arrow). (b) The resulting distribution of the electric field at fixed moment of time.

Here, we study the asymmetric excitation of high-index dielectric subwavelength nanoantenna by a point source, located in the notch at the nanoantenna surface [4]. The nanoantenna (Fig. 1a) is a spherical nanoparticle made of a dielectric material with a high dielectric constant. We observe the generation of the chiral near-field distribution (Fig. 1b), which is similar to that of a circularly polarized or rotating dipole. Using numerical simulations, we show that this effect is the result of a higher multipole modes excitation within the nanoparticle. Further, we employ this effect for the unidirectional launching of guide modes in the dielectric and plasmonic waveguides. Our results are important for the integrated nanophotonics and quantum information processing systems.

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Topological photonics in an electromagnetic continuum

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Photonic crystals have reshaped light-based technologies during the last few decades [1]. Remarkably, some years ago Raghu and Haldane discovered that the light propagation in photonic crystals may depend on some global topological properties determined by the manner how the light states are entangled in the spectral domain [2, 3]. The standard topological classification of photonic crystals relies on the fact that these structures are crystalline. The periodicity is of vital importance to guarantee that the underlying wave vector space is a closed surface with no boundary. In this talk, I will prove that it is possible calculate Chern invariants for a wide class of bianisotropic nonreciprocal electromagnetic continua with no intrinsic periodicity [4]. The nontrivial topology of the relevant electromagnetic continuum will be linked to the emergence of edge states. Moreover, it will be shown that photonic continua with the time-reversal symmetry can be separated into two distinct classes such that in a photonic band gap a given material is characterized by a topological number $D = 0$ or $D = 1$ [5]. This novel classification extends for the first time the theory of electronic topological insulators to a wide range of photonic platforms, and is expected to have an impact in the design of novel photonic waveguides that enable a topologically protected transport of optical energy.

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Topological metamaterials for light and sound

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The past three decades have witnessed the discovery of Quantum Hall Effect (QHE), Quantum Spin Hall Effect (QSHE) and Topological Insulators (TIs), which transformed our views on the quantum states of matter. These exotic states are characterized by insulating behavior in the bulk and the presence of the edge states contributing to charge or spin currents which persist even when the edge is distorted or contains impurities. In the last few years, a number of studies have shown that similar robust conducting edge states can be implemented in classical systems [1, 2, 3]. In this talk I will review development of this field with focus on photonic and acoustic topological structures with and without time-reversal symmetry that we have recently proposed [4, 5, 6]. I will discuss recent experimental realizations of topological order for electromagnetic waves with the use of bianisotropic metamaterials at microwave frequencies [4, 5]. New practical designs of photonic and acoustic topological insulators and their possible applications will be presented. I will show that photonic and acoustic topological systems, with deliberately created distributions of synthetic gauge fields, offer an unprecedented platform for controlling light and sound, e.g. by enabling routing and steering of waves along arbitrarily shaped pathways without loss or backscattering [6].

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Attenuated total reflection spectroscopy of hybrid optical surface waves in anisotropic metasurface

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Significant advance in the field of nanophotonics has been achieved with the help of metamaterials – artificially created composite structures, whose electromagnetic properties drastically differ from the properties of the natural materials. However, three-dimensional metamaterials are poorly compatible with planar technology, which is a significant obstacle for their applications in the optical range. One of the possible ways to overcome this problem is to use metasurfaces, a two-dimensional analogue of metamaterials [1]. Along with unprecedented control over propagation of bulk optical waves, metasurfaces can support surface waves [2].

In the framework of effective medium approximation, anisotropic metasurface can be described by a two-dimensional conductivity tensor [3, 4]. The dispersion relation can be directly derived from the Maxwell's equations and predicts coexistence of unusual surface waves with TE-, TM- and hybrid polarizations.

To implement such an anisotropic resonant metasurface with the desired optical properties we fabricated a square array of anisotropic gold nanoparticles on fused silica substrate using electron beam lithography. The geometrical parameters of the sample were optimized using finite-difference time domain simulation technique.

In order to directly observe surface waves supported by the metasurface we resorted to frustrated total internal reflection spectroscopy measurements in Otto configuration.The reflectance spectra were measured for different incident angles for both TE- and TM-polarizations and for two planes of incidence containing the main axis of the anisotropic metasurface. The acquired data fitted well theoretical predictions and allowed us to fully reconstruct the dispersion diagrams of surface waves propagating along two main axes of the metasurface. The experimental and theoretical data clearly demonstrated that the topological transition from elliptic to hyperbolic regime occurs at certain wavelength. We believe that our results open new ways for application of hyperbolic metasurfaces in optical and optoelectronic devices.

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Electromagnetic field visualizer based on wire metamaterial

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Wire metamaterials are materials composed of lattices of aligned metal wires embedded in a dielectric matrix [1]. The investigation of wire metamaterials has a long history, however, most of their important and useful properties have been revealed and understood only recently. A lens formed by array of wires provides a unique opportunity to transmit the near field of an object with super-resolution and reproduce the image at the lens back interface. Here we demonstrate the device based on a quarter-wavelength metal-backed wire lens which allows to visualize the near electromagnetic field of an object [2]. When the wires are attached to a metallic screen, the shortest resonant length of the wires is twice smaller than in the case of free-standing wires; thus, one may realize a quarter-wavelength wire lens in which the subwavelength imaging occurs at the screen plane where the image is encoded in the wires currents. The main problem we have solved here is the circuit design of the current detecting network. In order to detect the current in each wire, we use a high-frequency detector, which rectifies the received signal. Thereafter, all the signals received from the wires are multiplexed and fed to the microcontroller for digital processing. Microcontroller digitizes the analog signals and transmits them to a personal computer. The rersonal computer forms a raster image from the digital samples, where each pixel corresponds to a wire in the wire metamaterial. The pixel color indicates the current strength in the wire. The photograph of the visualizer designed for the operational frequency 1.8 GHz is presented in Fig. 1 (a). It consists of the array of 21 x 21 4.1 cm long brass wires arranged with 1 cm period. The wires are connected to metallic pads of printed circuit boards holding the electronic components of the detecting network and placed behind the metal screen. To experimentally investigate the vizualiser an antenna in form of a the flag has been fabricated and placed next to the wires. The obtained field distribution is demonstrated in Fig. 1 (b) in comparison with the simulated results.

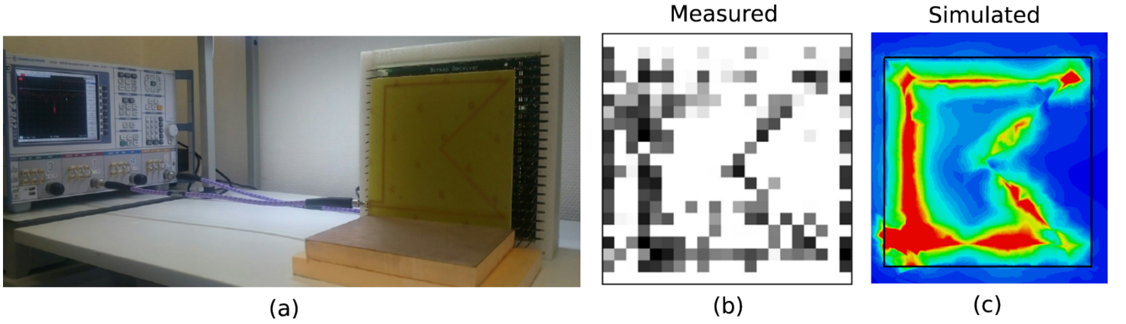

Fig. 1: (a) Photograph of the visualizer prototype. (b) Measured field distribution of the antenna excited by a vector network analyzer in the continuous wave mode at the frequency 1.8 GHz. (c) The simulated field distribution of the antenna.

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Self-Complimentary Metasurfaces: from Basic Equations to Practical Designs of Polarization Converters

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Metasurfaces have become useful tools to manipulate characteristics of electromagnetic waves. Usually, metasurfaces are periodic or quasiperiodic two-dimensional arrays of structured unit cells with subwavelength dimensions and periodicity. However, such structures effectively behave as optically thin sheets with macroscopic electromagnetic properties dependent on the unit-cell microstructure. Over the past several years many practical designs of microwave and optical devices based on metasurfaces have been demonstrated, which can be classified by their functionalities [1]. Among others, there were polarization converters (the devices converting a given polarization state of an incident wave to another polarization state of transmitted or reflected waves). Particularly, linear-to-circular polarization converters realized as metasurfaces are of a great importance. Such devices, despite of having negligible optical thicknesses, operate as artificial quarter-wave plates (see e.g. section 7.3 in [1]).

In this work we discuss the operation principles and practical realizations of linear-to-circular polarization converters based on a special class of *self-complimentary* metasurfaces. The last are thin sheets of metal patterned in such a way that these structures are identical to their complements (the inverse patterns), except for some translation smaller than the periodicity. The common symmetry of self-complimentary patterns satisfies several basic constrains for the macroscopic (averaged) fields simultaneously: the Babinet's principle, the electric sheet impedance boundary condition and the energy conservation law. As shown in [2], this leads to the unique property of self-complimentary metasurfaces: the transmission coefficients of two orthogonal linear polarizations have the phase difference of 90° at any frequency. This property guaranties the capability of linear-to-circular polarization conversion, which significantly simplifies the design of thin polarizers as compared to previous known approaches. Moreover, self-complimentary structures require only one patterned metal sheet, which allows microwave, submillimeter and terahertz realization, where the pattern in printed on one side of a dielectric substrate. By modifying shapes of unit cells a required frequency behavior of polarization conversion can be achieved.

In this work we explain the design principles of self-complimentary metasurfaces and demonstrate two particular designs of corresponding microwave polarization converters (one is narrowband and the other is wideband). We discuss the results of measurements in an anechoic chamber, which are in good comparison with numerical simulations.

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The wideband spherical Luneburg lens based on an artificial-dielectric microwave metamaterial

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Lenses play an important role in various technical applications both in optical information processing systems and in radiofrequency devices acting as elements of aperture antennas. Examples of using various types of lenses are astronomical instruments for observation of cosmic processes in radio, terahertz and optical frequency ranges, and general experimental tools such as spectroscopes, coherent detectors, radiation sources. Among different types of lenses, the special place belongs to the transformation optics lens, using the material filling with a spatially non-uniform refractive index. Spherical Luneburg lenses have the unique property of forming a perfectly parallel beam out of rays from a point source on the focal sphere [1]. Spherical Luneburg lenses are insensitive with respect to the direction of an incident wave. In the microwave range this property allows to realize multi beam antennas without phase errors [2], which makes them important to use in problems of radar and radio communications note that such properties cannot be realized in lens antennas of other types. Similar lenses are very attractive for prospective highly directional microwave antennas, however their practical application is accomplished due to high weight of the lens and complexity of the conventional multilayer realization [2]. Metamaterials are structures with subwavelength periodical dimensions of unit cells with defined properties. With metamaterials one can realize material properties not inherent to nature materials. In particular, metamaterials open new possibilities to design using the principles of transformation optics.

In this work we show the results of numerical and experimental investigation of the Luneburg lens based on the metamaterial composed of radially diverging dielectric rods. The lens is composed of identical dielectric rods arranged periodically so that the adjacent rods touched each other near the lens center and held the sub-wavelength separation at the periphery. The dielectric rods had non-uniform cross-section area, which is a function of the distance r to the lens center. This function was optimized based effective permittivity theory for a medium of dielectric rods [3]. This solution allows to reduce the lens's weight and significantly simplify manufacturing. In this work we investigate material parameters of metamaterial based on the structure of radial diverging dielectric rods and create a numerical model of Luneburg lens based on this metamaterial. Also we discuss the influence of spatial dispersion effects on the lens's properties. Finally, we present the experimental results for the manufactured of Luneburg lens working in X-band (8 - 12 GHz).

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Experimental demonstration of microwave metasurface

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Metasurfaces are 2-dimensional metamaterials that provide excellent opportunity for electromagnetic wave control while being compact and relatively easy to fabricate [1]. The functionality of all-dielectric metasurfaces is typically based on high values of a dielectric permittivity. On the contrast to conventional high-k microwave ceramics, one of the most abundant, easily reconfigurable and by default nature-friendly material is water. High permittivity and easy volume reshaping of liquid water are remarkable properties for designing microwave tunable metamaterials with advanced functionalities. Andryieuski et al.[2] proposed to use the properties of water for tunable transmission of electromagnetic waves through a system of partially filled water meta-atoms. In such configuration the water-based metamaterials can be definitely considered as the simplest and potentially the cheapest realization of a tunable metamaterial or metasurface.

The metasurface under study is composed of unit cells periodically arranged in a square lattice with period d=6 cm. An individual unit cell consist of an empty elliptical cylinder half filled with water. The elliptical cylinder has the following parameters: major axis a=2.5 cm, minor axis b=1 cm and height (or thickness) h=1 cm. Distilled water with permittivity $\epsilon = 78+i\cdot 4.7$ was used as liquid dielectric.

With the metasurface clockwise rotation up to 90^o the water flows and changes its shape. In this manner the metasurface is dynamically tunable with its transmission depending on the rotation angle. To demonstrate the tunability, we specifically characterized the metasurface transmission in dependence on rotation around orthogonal axis.

We numerically and experimentally studied the metasurface transmission properties for a horizontally and circularly polarized plane wave. Under the 0^o rotation angle the minimum of the transmission coefficient magnitude is 0.35 at the frequency near 1.2 GHz. Rotation of the metasurface increases the transmission coefficient up to 0.95.

We also studied experimentally the tunability of the water based metasurface under the vertically and circularly polarized plane wave excitation. The results of simulations were in good agreement with simulated.

In conclusion, we have assembled and characterized extremely simple and cheap tunable metasurface for the microwave frequency range. The demonstrated range of transmission variation is relatively modest, between 0.4 and 1.0 in magnitude (from -8 dB to 0 dB), but it can be well expanded by considering, for example, other shapes of the water inclusions with larger asymmetry. We believe that the proposed architecture of tunable metasurfaces can find a wide application in microwave technology, especially for demonstration and cost efficient prototyping of functional artificial electromagnetic surfaces.

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Optical properties tuning of hybrid nanoantennas

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The combination of plasmonics and all-dielectric nanophotonics in the concepts of metaldielectric (hybrid) nanophotonics has allowed to utilize the advantages of both these directions (strong localization of light, artificial magnetic optical response and unique scattering properties) in the form of hybrid nanostructures (nanoantennas and metasurfaces) [1, 2]. The unique properties of hybrid nanostructures mostly depend on the spectral overlapping of their optical modes in metal and dielectric nanoparticles. Therefore, the ability to tune optical properties of nanosystems is the key factor towards development of all-optical data-processing components for integration in optical circuits.

Recently, we have proposed a novel method for fabrication of ordered asymmetric metaldielectric (Au/Si) nanoparticles [3]. Here, we present a original concepts of reversible and non-reversible precise manipulation by the optical properties of the hybrid nanostructures. The feasibility of both concepts is confirmed by numerical modeling and demonstrated experimentally. The non-reversible tuning of hybrid nanostructures is attained via selective laser-induced reshaping of the metal components without affecting the dielectric ones. We apply this approach for the demonstration of the local optical properties tuning of hybrid metasurfaces by shifting of spectral position of resonant transmittance on 250 nm. The reversible technique is based on electron-hole plasma generation in the dielectric component of the hybrid nanodimer, leading to modification of its optical properties. This technique was recently demonstrated as a means of optical tuning of all-dielectric nanostructures [4]. Here, we experimentally demonstrate 15% tuning of transmittance of a single hybrid nanodimer by femtosecond laser pulses. The received results are in good agreement with predictions of developed analytical model.

Our investigations open a possibility for application of hybrid nanophotonics in advanced optical and biomedical applications as well as creation of storage elements for optical computer systems.

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Self-Adjusted All-Dielectric Metasurface for Enhanced Third Harmonic Generation

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Generation of high-order harmonics from ultrathin nanostructures and metasurfaces is a prospective way for development of fs-pulsed light sources at new frequencies, which are inaccessible by other methods. The advantage of the approach is that it does not require phase matching, and the generated pulses are short in time domain without additional pulse compression [1]. However, fabrication of large-scale planar structures by lithography-based methods is expensive, time consuming, and requires complicated preliminary simulations to get the most optimized geometry for the highest nonlinear response. Here, we propose a novel strategy for self-assembled fabrication of large-scale resonant metasurface, where incident femtosecond laser pulses adjust initial silicon film via specific surface deformation to be as resonant as possible for a given wavelength. The self-adjusting approach eliminates necessity in multistep lithography and designing, because interference between the incident and the scattered parts of each laser pulse "imprints" resonant field distribution within the film via its localized heating and deformation. The self-adjusted metasurfaces demonstrate high damage threshold (10^{12} W/cm^2) and highly efficient frequency conversion from near-IR to deep UV. The conversion efficiency is up to 30-fold higher as compared with nonresonant smooth Si films. The resulting metasurfaces allow for generation of UV femtosecond laser pulses of duration < 40 fs at a central wavelength of 270 nm with high peak and average power (10^5 W and 1.5 μW, respectively). The results pave the way to creation of ultrathin nonlinear metadevices working at high laser intensities for highly efficient deep UV generation.

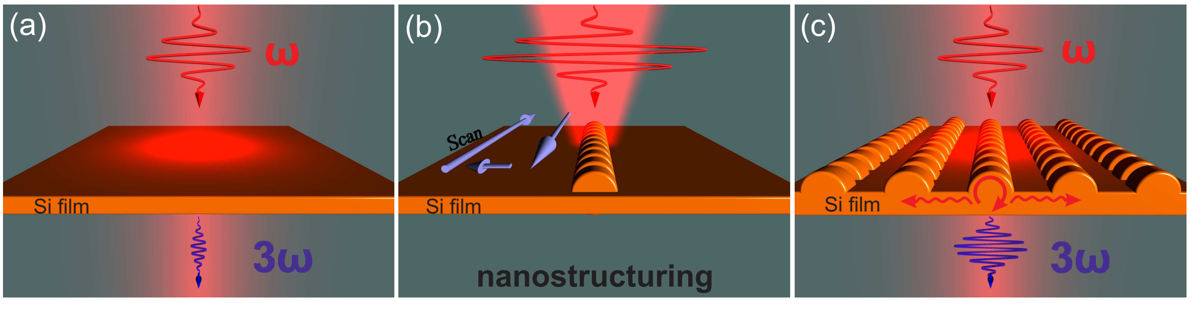

Fig. 1: Schematic views of third harmonic generation from smooth (A) and nanostructured (C) Si film. (B) Illustration of the principle of Si film laser-induced nanostructuring.

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Enhancement of magnetic and electric fields with silicon nanodimers

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High refractive index dielectric nanoparticles have risen to prominence in the nanophotonics toolkit for ultimate control of light [1, 2]. Compared to plasmonic nanoparticles, dielectric nanostructures have negligible ohmic losses, demonstrate larger far-field scattering cross sections and possess both electric and magnetic optical responses, which can be tuned through a broad spectral range. As optical nanoantennas, dielectric nanostructures can provide high quantum efficiency in the absence of quenching of radiative emission [3, 4].

The nanodimer geometry offers the ability to further engineer the optical response of these dielectric structures. Electromagnetic properties of high-index dielectric dimers have been studied numerically [3, 5] and experimentally in the visible spectral range via dark-field [6] and cathodoluminescence [7] spectroscopy.

In this work we present first experimental demonstration of near electromagnetic field enhancement in the gap of resonant silicon nanodimer at visible frequencies [8]. The response of the system has been studied as a function of wavelength, polarization, and gap. The near-field measurements show a very good agreement with the numerical simulations. When the simulated near-fields are broken down into their components, it is confirmed that the resonant near-field signal enhancement measured is strongly magnetic in nature, for both polarizations.

Additionally, we have conducted a complete analysis of the modes excited inside the dielectric nanodimer system by means of the multipole decomposition. This analysis reveals the excitation of a toroidal dipole moment which interferes with the Cartesian electric dipole moment resulting in a dip in the total electric dipole radiation. This is the first report of toroidal dipole excitation in dielectric nanodimer antennas.

The studied dimer system is the basic building block for many nanophotonics systems. Our results lay the groundwork for engineering of the magnetic field response with high-index dielectric nanostructures at optical frequencies.

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Raman Scattering from Crystalline Silicon Nanoparticles Enhanced by Mie Resonances

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Raman scattering of light is an electromagnetic effect which has found many different applications including sensing, optical amplification and lasing[1]. Traditionally, plasmonic nanoparticles have been used for applications requiring enhanced Raman scattering, however because of dissipative losses, plasmonic structures suffer from parasitic heating, somewhat limiting their applicability. Recent studies in high-index dielectric nanoparticles have paved the way towards all-dielectric resonant nanodevices[2], which lack plasmonics' problems with dissipative losses.

Many semiconductor materials, including crystalline silicon, demonstrate their own Raman signals. Also, crystalline silicon nanoparticles exhibit Mie-type electric and magnetic resonances[3], which can be used to enhance Raman scattering from the nanoparticles. Previous studies of Raman scattering by silicon nanostructures have only considered dense clusters of nanoparticles[4] or large bulk waveguide structures.

Here we present an experimental and theoretical studies of enhanced Raman scattering from single crystalline silicon nanoparticles, fabricated by our laser-transfer technique[4]. Comparison of Raman scattering from resonant particles to scattering from their non-resonant counterparts shows at 140-fold increase in Raman signal. We have shown theoretically and demonstrated experimentally, that the strongest enhancement of Raman scattering occurs in the vicinity of the nanoparticles' magnetic resonances. The efficiency of the enhancement is related to the different nanparticles' resonances' Q-factor and electric field confinement in the bulk of the nanoparticle, favoring the magnetic dipole resonance.

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From high-Q magnetic dipole scattering to broadband electric field localization by silicon nanoparticle on metal

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High refractive index dielectric nanoparticles are attracting significant attention due to their unique properties that stem from the presence of both magnetic and electric dipole responses in the visible spectral range[1, 2]. The interplay of these resonances in combination with inherently low level of losses has already inspired all-dielectric-based solutions for superdirective nanoantennas, sensors, metasurfaces for efficient wavefront control and beam shaping, metadevices granting giant enhancement of non-linear effects, etc. Still, high radiative losses limit the maximum Q-factor of the low-order resonances of dielectric nanoparticles. This forces to use higher order modes for applications requiring field enhancement, which means the increase of the resonator size. Therefore, an efficient way to control the quality-factor of the dipole resonances of high-index nanoparticles could open new possibilities for integration of dielectric nanostructures in nanophotonic devices.

In this work, we discover remarkable modifications of *normal* (perpendicular to the substrate surface) magnetic and electric dipole responses of a silicon nanosphere driven by gold substrate.

A 170 nm silicon nanosphere fabricated by femtosecond laser ablation of Si wafer was placed on a gold substrate (40 nm gold layer on a glass plate) via nanomanipulations under electron beam. We studied the scattering properties of the nanoparticle using a polarization-resolved dark-field microscope with independent excitation (side) and collection (upper) optical channels[3]. In this work, we introduced a linear polarizer in the collection channel. This allowed us to selectively detect the scattering signal from the induced normal dipole components, which is either azimuthally or radially polarized, while linearly polarized scattering from transverse dipole modes was filtered out.

The experimental spectra for a 170 nm silicon nanosphere reveal two remarkable features. The first one is the drastic substrate-driven modification of the quality factor of normal magnetic dipole response ($\mathbf{m}_z$), which reaches an exceptional value of 25 for gold substrate. At the same time, the scattering signal for cross-polarized configuration under p-polarized excitation is very low, which indicates the reduction of the radiation losses of $\mathbf{p}_z$ mode.

We find the measured spectra to be in excellent agreement with the analytical results obtained via the Green's function approach[4] and the data from full-wave numerical simulations. The latter also reveals strong field enhancement associated with both normal magnetic and normal electric dipole modes, which can be utilized for enhanced sensing and augmentation of nonlinear processes.

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Photo-induced phenomena on the surface of glassy semiconductors studied with the femtosecond resolution in time

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A time-resolved pump-probe method has been applied to study Kerr non-linearity, charge carriers kinetics and permanent change of refractive index in chalcogenide glasses of the system As-S-Se.

Permanent change of refractive index induced in optical materials by the ultra-short laser pulses can be used for creation of submicron-size optical features. At present, waveguides with the highest contrast of refractive index were written in chalcogenide glasses [1]. These glassy semiconductors transparent in the mid-IR have large Kerr constants, which are greater than that of fused silica by two to three orders of magnitude. However, non-linear optical response and photosensitivity of non-crystalline semiconductors are still weak understood [2]. Due to energy levels in a bandgap (gap states) the fundamental absorption band (FAB) edge of a non-crystalline semiconductor has a spectral range of exponential decay (Urbach tail). Irradiation of a chalcogenide glass by a CW laser at the Urbach tail is usually used for photo-structural modifications, which are known as photodarkening.

Time-resolved interferometric pump-probe method [3] was applied to study the non-linear optical response in bulk samples of chalcogenide glasses of the system As-S-Se near their bandgap frequencies [4]. This method enabled us to evaluate the non-linear optical coefficients of refraction and absorption at the peak wavelength of 790 nm of a 50 fs pump pulse and to study charge carriers kinetics over time intervals up to one nanosecond at the pump energy E ranging from 300 nJ to 15 μJ. Our experiments have revealed that the kinetics depended on where a glass sample was illuminated, near or far from its FAB edge. In a sample illuminated at its Urbach tail, electrons trapping time did not depend on E manifesting direct transition of electrons to (or through) the gap states. At relatively low E, linear dependence of the refractive index change Δn on the pump pulse intensity (< 100 GW/cm^2) has been obtained. At higher intensities, the photosensitivity was larger and depended on the glass composition. In the measurements far from the FAB edge, the electrons trapping time decreased with E increase. An energy threshold for the refractive index permanent variation has been found.

Due to mild focusing of the pump laser beam on a sample, the refractive index was modified near the sample surface. By numerical modelling of the charge carriers kinetics, spatio-temporal distribution of Δn over the sample volume has been evaluated by using the Drude-Lorenz model [3] and the quasi-plane laser beam approximation. In the volume, a permanent Δn gradually varies from its maximum on the sample surface to zero over a depth of less that 100 μm. Shape of the Δn gradient profile depends on magnitudes of two- and single- photon absorption coefficients and material parameters of the glass compositions such as rate of charge carriers recombination and cross-section of electrons trapping.

Tailoring of the glass composition and/or pump laser wavelength can be used to manage shapes and dimensions of the modified structures, to increase Δn maximum.

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Plasmonic nanoguides: fundamentals and applications

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Abstract

Modern communication systems dealing with vast amounts of data at ever increasing speed started to progressively stronger experience the fundamental limitations imposed on the existing electronic and optical technologies. Specifically, *nm*-sized electronic (metallic) circuits are inherently slow due to *RC*-delay times, whereas optical (dielectric) circuits having enormous information capacities are essentially *μm*-sized due to diffraction effects. It is fascinating to note that electromagnetic modes supported by metal/dielectric interfaces were found to be beating the diffraction limit while upholding the optical bandwidth. These modes, in which optical fields are coupled to electron oscillations, are usually called surface plasmons (SPs) and are characterized by the wavelength that is always shorter than the wavelength in the dielectric, exhibiting thereby subwavelength confinement. It should be emphasized that not all SP modes allow for unlimited squeezing in the cross section perpendicular to their propagation (i.e., going “nano”), a property that is imperative for realization of plasmonic circuits combining the compactness of electronics with huge bandwidth of optical networks.

Here, we concentrate on SP guiding geometries ensuring truly nanoscale field confinement and review the current status of this very young but rapidly growing area of nanoplasmonics. Both fundamental physics and application aspects are overviewed in detail. After briefly reviewing various SP guiding configurations the results of our investigations of subwavelength photonic components utilizing SP modes are overviewed [1-6], demonstrating first examples of *ultracompact* plasmonic components that pave the way for a new class of integrated optical circuits.

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Nano-tapers: squeezing light in a dielectric nano-guide for overtone spectroscopy

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Nano-guides benefit from huge evanescent field, therefore they are widely used in applications such as: optical trapping, sensing, evanescent coupling and more [1], however their advantages in overtone spectroscopy have never been explored. Here we explore the evanescent fields of tapers for spectroscopy of organic molecule N-Methylaniline's amine (N-H) band at $\lambda_{NH} = 1.496\mu$m, since the molecule has an electric dipole moment at λ_{NH} calculated with computational chemistry software Spartan 14: $\mu = \sum_{n=1}^{N} e_n r_n = D$ with e_n point charges at positions r_n. We consider two configurations embedded in 33% N-Methylaniline in hexane mixture: (a) silica micro-fiber and (b) S_3N_4 rib waveguide on a 2 μm silica substrate having guiding layer of 700×700 nm and tapered region of 300 nm width and 700 nm height. We calculate the mode profiles have using fine element method using COMSOL Multiphysics 5.2. Figure 1a shows the geometry of tapered fiber radius of 1μm. Figure 1b and Figure 1c show the 3D mode profile colormaps and the crossection accordingly. Figure 1d shows the geometry of the tapered-waveguide. Figure 1e and Figure 1f show the mode profile and crossesctions (brown) at $x = 0\mu$m and at (green) ($y = 350$nm) respectively. We define the complex index of the molecule as $n' = n + j\kappa$, κ has been calculated from the absortpion spectra reported elswhere [2] with concentration of 33% molecule diluted in hexane. The n was calculated using Kramers-Kronings relation implemented here using Hilbert transform defined in Eq. 1.

$$n(\omega_0) = 1.43 + \frac{2}{\pi}\int_0^{\infty} \frac{\omega\kappa(\omega)}{(\omega^2 - \omega_0^2)} d\omega. \qquad (1)$$

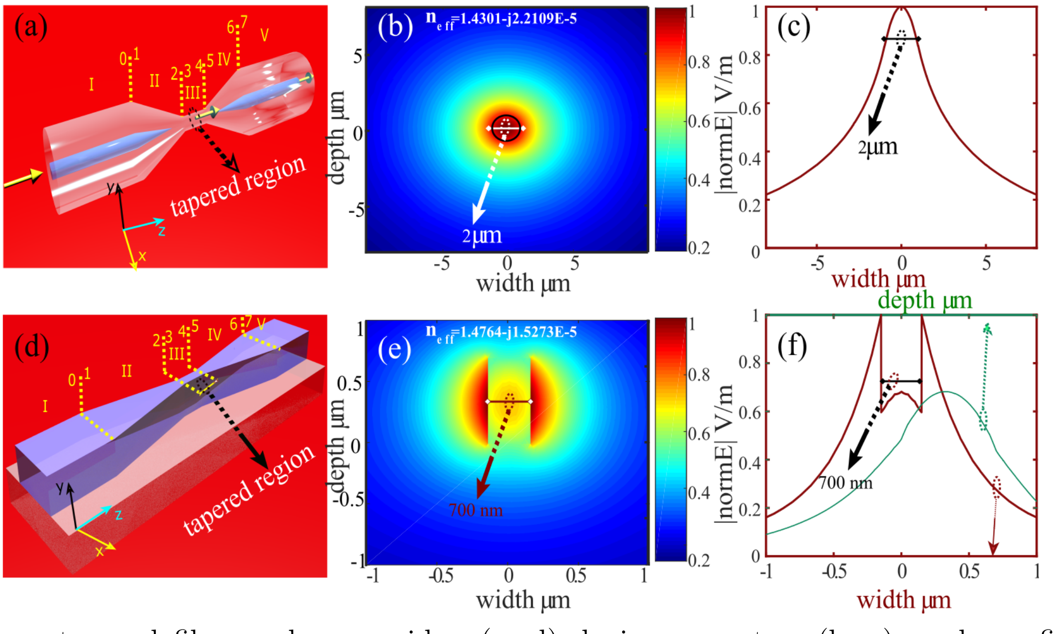

Fig. 1: Nano-tapered fiber and waveguide. (a, d) device geometry; (b, e) mode profiles; (c, f) crossesctions.

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Inverse dispersion method for calculation of photonic band diagrams: Application to the transition from photonic crystals to all-dielectric metamaterials

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Dielectric photonic crystals and metamaterials represent two different classes of artificial media which can be composed of similar structural elements. A periodic photonic structure transforms into a all-dielectric metamaterial when the Mie gap opens up below the lowest Bragg bandgap where the homogenization approach can be justified and the effective permeability becomes negative [1]. The question is how to distinguish between Mie and Bragg bandgaps in complicated photonic band diagram when parameters of the structure, such as permittivity and lattice constant, vary continuously.

To solve this problem, we proposed an inverse dispersion method for calculation of photonic band diagram of periodical media with arbitrary dielectric function. The method also allows calculating both propagating and evanescent modes. We reduce Maxwell's equations to the problem with the eigenvalue k, while ω is considered to be a real parameter. We call proposed method the inverse $k(\omega)$ problem instead of the direct $\omega(k)$ problem. Using this method we resolve two limitation of the direct approaches. The first one is related to the strong frequency dependence of $\varepsilon(\omega)$. To realize numerical techniques, ω should be excluded from the operator but it can be proceeded only for the restricted classes of $\varepsilon(\omega)$ function. The second one is that the traditional methods are not aimed to calculate the evanescent modes. In contrast, in realization of the inverse method k should be excluded from the operator. Fortunately, in most cases the spatial dispersion $\varepsilon(k)$ is negligible and the dielectric function does depend on the wave vector that is treated as the eigenvalue.

We consider the 2D square lattice of dielectric cylinder acts as a photonic crystal at the low dielectric contrast and as a metamaterial at high enough contrast and special structural conditions [1]. For such structure, we able to study prohibited evanescent modes by setting ω within the bandgap and reveal whether the mode originates from the localized Mie resonance and the structure can be homogenized or not. We also find that the Mie features make the band diagram disconnected at the X point. Additionally, using the results of the inverse dispersion method we can separate Bragg and Mie gaps by introducing small amount of losses. The modes forming Bragg gaps does not change they direction, while modes forming Mie gaps shows repulsive behavior.

We notice that the proposed inverse dispersion method is not restricted to the photonic structures only, rather it is applicable to any waves in periodical media: electrons, phonons, magnons etc.

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Chirality in nanophotonic waveguides with embedded quantum dots

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We demonstrate the intrinsic chirality of electromagnetic fields and resulting spin dependent unidirectional emission from quantum dots embedded in nanophotonic waveguides both in experiment and in numerical simulations. The phenomenon arises from strong localization of the electromagnetic fields on the nano-scale; this leads to the appearance of longitudinal components of the electric field with odd symmetry in addition to the transverse field component. The GaAs nanobeams employed thus support circularly polarized fields in the plane of propagation. The circular polarization of the photon emitted from an embedded InGaAs quantum dot defines the direction of propagation in the waveguide (see Fig.1). Thus quantum dot spin to photon-pathway encoding and spin transfer along the waveguides are achieved. Unidirectional coupling is observed for circularly polarized quantum dot states split in magnetic field (see experimental scheme in Fig.1b and spectra in Fig.1b inset) and is also confirmed in simulations (see Fig.1a) and by implementation of quantum dot registration technique. Experimental comparisons of the single mode nanobeam waveguides with photonic crystal waveguides [1] reveals advantages of the nanobeams. In addition we explore polarization independent excitation schemes that allow initializing the spin in the quantum dot (see Fig.1c) thus demonstrating path-to-spin conversion. We conclude that nanobeam waveguides with embedded position controlled quantum dots open the way for the creation of chiral spin optical information processing circuits on-chip [2].

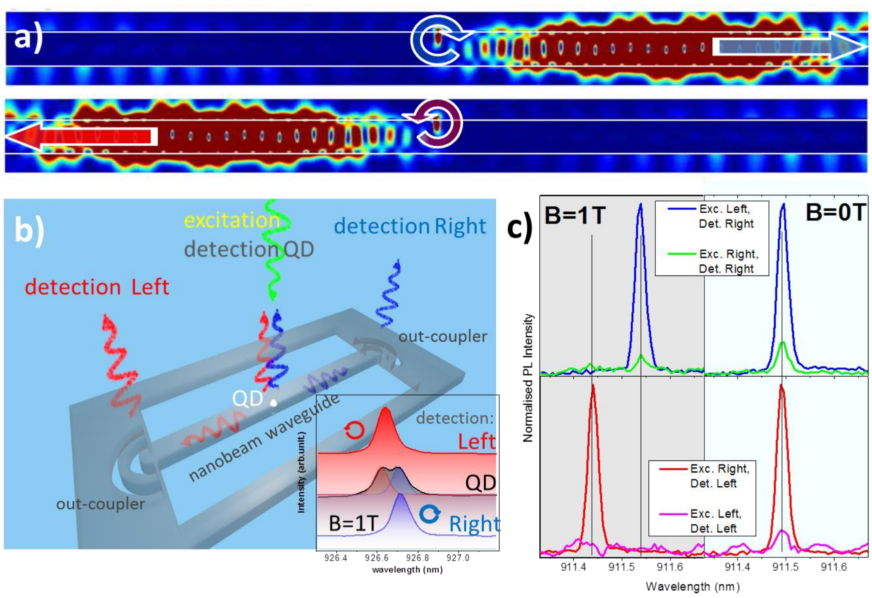

Fig. 1: a) emission from circularly polarized dipoles in a waveguide simulated in FDTD; b) spin readout scheme of quantum dot states in a nanobeam waveguide with spectra recoded from three collection points; photon helicity and propagation directions are shown with arrows; c) spin initialization spectra.

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Meta-Atoms on Merry-go-round

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Electromagnetic scattering in accelerating reference frames inspires a variety of phenomena, requiring employment of general relativity for their description. While the 'quasistationary' analysis could be applied to slowly-accelerating bodies as a first-order approximation, the scattering problem remains fundamentally nonlinear in boundary conditions, giving rise to multiple frequency generation.

Here electromagnetic scattering from axially rotating subwavelength (cm-range) meta-atoms, will be discussed. Rigorous theoretical analysis, based on Hallen integral equation, is employed for deriving the currents induced on scatterers at rest and a set of coordinate transformations, connecting laboratory and rotating frames, is applied in order to predict the spectral positions and amplitudes of the frequency comb peaks. Experimental results will be presented in support of theoretical predictions. In particular, highly accurate 'lock in' detection schemewill be demonstrated. It enables factorization of the carrier and observation of more than ten peaks in the nonlinear frequency comb (micro-Doppler shifts).

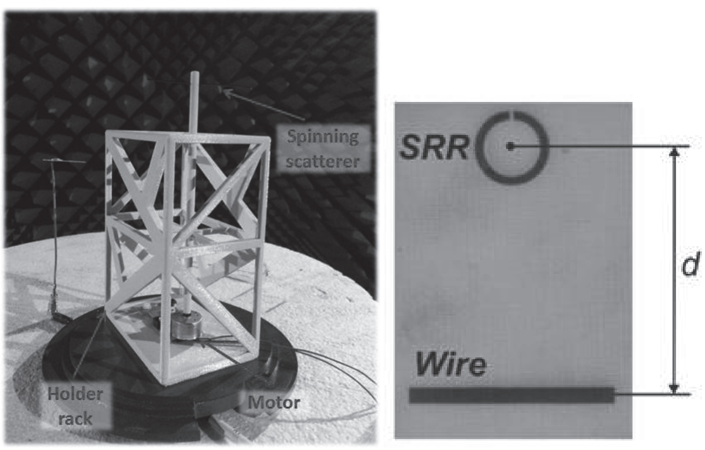

Fig. 1: (Left) Photograph of experimental setup for studies of scattering from spinning objects [1]. (Right) Photograph of hybrid magneto-electric particle (meta-atom) with symmetric forward and asymmetric backward scattering characteristics [2].

Unique spectral signature of micro-Doppler shifts could enable resolving an internal structure of the scatterers and mapping their accelerations in space, which is valuable for a variety of applications spanning from targets identification to stellar radiometry.

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New insights into an old topic: The Multipole Expansion

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Quantifying the optical properties of artificial meta-atoms in terms of multipole moments is a key quantity to understand their optical action and to consider them in a broad range of applications in the slip stream of nanoplasmonics, optical antennas, and metamaterials. The multipole moments, in general, represent elementary excitations into which the response of the meta-atom upon stimulus by an external illumination can be expanded. Usually, two approaches are used for this purpose. In a first one, the scattered field is taken and projected onto the vector spherical harmonics, being eigenmodes to the wave equation in spherical coordinates. Alternatively, the currents (either conductive or displacement current) induced in the meta-atom can be expanded in an orthonormal base. Since the radiated fields are completely determined by the current sources, the expansion of the currents must contain all the information that can be obtained by the expansion of the fields. However, this is usually obscured by an additional small argument approximation, valid only for scatterers having a size much smaller than the wavelength, that is done to simplify the expressions for multipole moments on the base of the current distributions. The emerging approximate expression, e.g. for the magnetic dipole moment, read as

$$\mathbf{b}_1(\omega) \propto \int d^3\mathbf{r}\ \ [\mathbf{r} \times \mathbf{J}(\mathbf{r}, \omega)]$$

This small argument approximation, however, ceases to be applicable for most meta-atoms of interest. It leads to erroneous predictions of the multipole moments and, most notably, causes the appearance of seemingly new phenomena such as dynamic toroidal multipole moments.

Here, we outline the derivation of new expressions for the multipole moments on the base of the current distributions from first principles that are exact and simple, i.e. comparable in complexity to those approximate expressions valid only for small objects and identical to those multipole moments extracted from the scattered field. For the magnetic dipole moment they read, e.g., as

$$\mathbf{b}_1(\omega) \propto \int d^3\mathbf{r}\ \ [\mathbf{r} \times \mathbf{J}(\mathbf{r}, \omega)]\, j_1(kr)$$

More general expressions will be presented at the conference, even though most important will be expressions for the dipolar and quadrupolar contributions. We show how these new expression provide more accurate predictions to analyse meta-atoms. This has implications, and we will discuss this, on the ability to predict effective properties of metamaterials, to study the optical force acting on meta-atoms, and to study the response from meta-surfaces. Our results can be applied in the many areas where the multipole moments of current sources are used.

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Mutual excitation of two nested 2D periodic chains and excitation transfer along linear chain of plasmonic particles

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Aggregates of nanoparticles are particularly attractive for medical and nanobiotechnological applications owing to plasmon resonance phenomena. In particular, a new trend in modern medicine is based on the introduction of the nanoparticles into biological tissue with the aim, for example, to visualize cells, drug delivery to target cells, labeled cells hyperthermia without heating surrounding normal tissue, and other applications. The last issues relate to the use of activated semiconductor nanoparticles for brain stimulation [1] without using the conventional complex wire bonding. It is known that metallic nanoparticles with plasmonic resonance being introduced into biological tissue, may unite as finite clusters obeying specific optical eigenmodes or line up to transfer excitation between clusters. Sufficiently well studied collective plasmon resonances in extinction spectra of metal nanoparticle clusters in the approximation of dipole and quadrupole scattering of the incident electromagnetic waves by nanoparticles [2]. Current problems may be formulated as: (i) collective modes that can be excited in nanoparticles clusters with different shape, (ii) excitation transfer along linear particle chain. In this way, in our opinion, can be obtained by physical justification brain stimulation [1] using nanoparticles and without the use of wire connections; (iii) excitation transfer between the inner and outer parts of the finite square lattice of nanoparticles that may help simulate the latest result of the dynamic interplay of several large-scale neural networks of the brain [3].

We currently present simple analytic and physically transparent results for the problem solution of collective modes exciting inside two dimensional circular clusters and the problem excitation transfer along one dimensional linear array of coupled small plasmonic spherical particles. The results are obtained with the aid of equations' system for self–consistent currents excited inside particles by incident electromagnetic wave field. For circular cluster of particles the coupling matrix between their currents becomes under definite conditions of such favorite properties that enables one immediately to write out the Bloch-like eigenmodes with corresponding eigenfrequencies and their halfwidthes. What is more we get also a simple analytic expressions for coupling factor between inner part of a square structure arranged in a circular shape and its bound part. Considering linear array of particles we use a closest neighbor interaction approach which makes the linear array like the electric filter. In this approximation an analytic expression are obtained for extinction rate of exciting currents' transfer depending on array particles number and for resonance filtering frequencies.

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Waveguide modes in one-dimensional magneto-photonic crystals

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We present theoretical and experimental study of waveguide modes propagation in one-dimensional magneto-photonic crystals (MPC) with in-plane magnetized layers. Two types of MPCs were considered: non-magnetic photonic crystal with magnetic dielectric film on top (sample 1), and MPC, were a magnetic dielectric is used as one of the layers within the period of the PC (sample 2). Theoretical dispersions of the modes were obtained via transfer matrix method [1], extended for the transverse magnetization case [2,3]. Experimentally observed dispersions are in good agreement with the theoretical and numerical modeling for both types of MPCs (Fig. 1). It is theoretically shown the propagation constants of the TM waveguide modes are sensitive to transverse magnetization reversal, and, as a result, the magneto-optical Kerr effect has experimental peculiarities at modes resonant wavelengths [2].

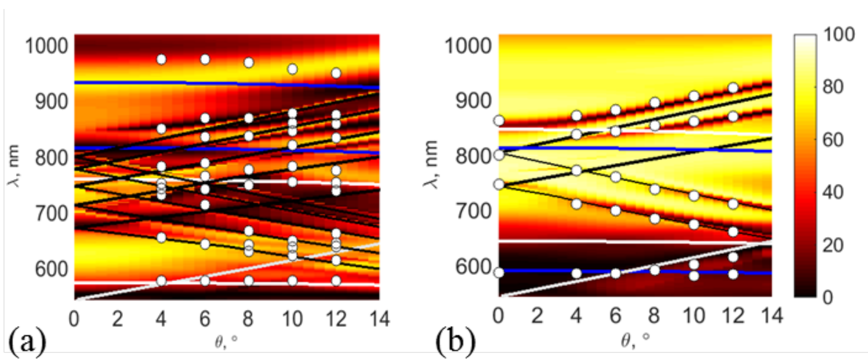

Fig. 1: The contour plot of the reflection of the sample 1 (a) and sample 2 (b) via wavelength and angle of incidence at the TM-polarization obtained with Rigorous Coupled Wave Analysis (RCWA). Colored lines represent the dispersions calculated from the transfer matrix approach. Waveguide modes excited at m=0, ±1 (blue, black lines, respectively), propagation constant of surface plasmon polaritons excited on the border the air / gold (gray lines). White circles point out the positions of the resonances obtained experimentally. Light is TM-polarized.

The work is supported by the Russian Presidential Grant MD-5763.2015.2.

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Full control of the spin angular momentum of light in the plane of anisotropic metasurface

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The studies of the surface waves have recently gained a new twist since it has been shown that they possess the unconventional spin angular momentum perpendicular to their propagation direction, which lies in the plane of the interface [1, 2]. It is contrary to the electromagnetic waves in free space, for which spin angular momentum is always collinear to the propagation direction. Therefore, spin angular momentum can be either only pure longitudinal for the plane waves or pure transversal for the surface waves. In this work we proposed a way to realize the tuning of spin angular momentum direction and its absolute value continuously – from pure transverse to pure longitudinal.

We considered anisotropic metasurface, which can support the hyperbolic regime. We described it within conductivity tensor in local approximation. It was shown that the spectrum of surface waves localized at such metasurface consists of two modes of hybrid TE-TM polarization [3]. Polarization can change from linear to elliptic or circular depending on the wave frequency and propagation direction. This unusual hybrid polarization results in emergence of longitudinal component of the spin angular momentum. Thus, spin angular momentum, which is the vector sum of transverse and longitudinal components, is directed at certain angle β with respect to the direction of surface wave propagation k_z (Fig. 1). Moreover, it can be easily tuned changing the the wave frequency and propagation angles, which can be expressed through polarization parameter m.

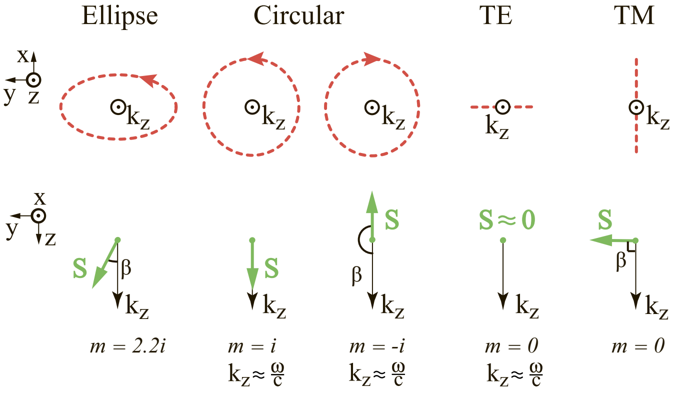

Fig. 1: Polarization of hyperbolic plasmons for different polarization parameters m with corresponding angles β between plasmon propagation and spin angular momentum directions.

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Bound state in the continuum in the one-dimensional photonic structures

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Optical bound states in the continuum (BIC) are infinitely high-Q states with energies lying above the light line of the surrounding space. The BIC was firstly proposed for quantum mechanical particle by von Neumann and Wigner in 1929 [1]. Optical analogue of BIC was firstly proposed by Marinica et al [2]. Experimental observation of BIC was demonstrated in Ref. [3]. Such high-Q states are very promising for many potential applications ranging from on-chip photonics and optical communications to biological sensing and photovoltaics.

In this work we theoretically and experimentally demonstrate CMOS-compatible one-dimensional photonic structure based on silicon-on-insulator wafer with optical BIC at telecommunication wavelengths. Excitation of optical BIC from free space is possible due to sample imperfections which are always present. The design of the structure and the dispersion of the leaky mode are shown in Fig. 1(a). Figure 1(b) shows the dependence of Q-factor of the leaky mode on wavenumber. The sharp peaks correspond to optical BIC.

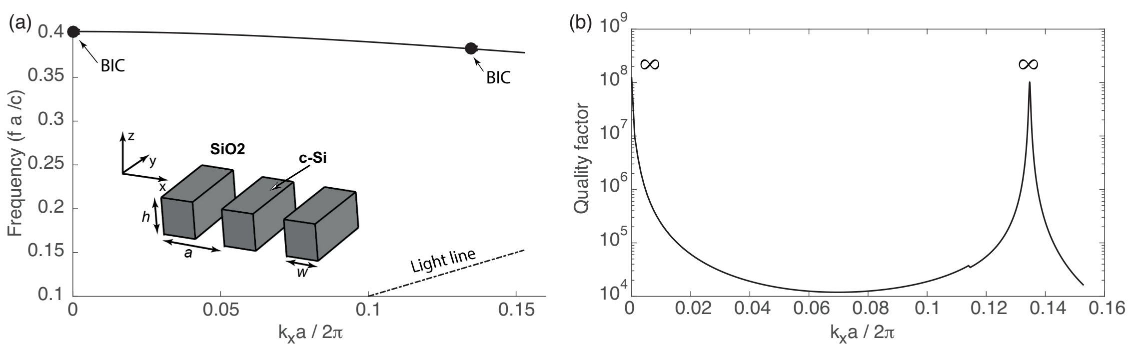

Fig. 1: (a) Dispersion of the leaky mode in 1D photonic structure. The insets show design of the structure. (b) Dependence of Q-factor of the leaky mode on the wavenumber. Both figures show results of simulations.

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Enhanced Magneto-Optical Effects in Active Plasmonic Nanostructures

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Ample opportunities provided by the plasmonic nanostructures find their applications in numerous fields of science. The properties that are weak or even absent in bulk natural materials become apparent and, sometimes, leading in specially designed nanostructures. For instance, the effective excitation of the surface plasmon polaritons (SPPs) [1] ensures the strong localization of the electromagnetic field and an increase of its intensity at the metal-dielectric surface. As a result, the light-dependent features can become stronger. In particular, the magneto-optical (MO) properties can be enhanced 10 times by a resonant excitation of SPPs in magnetic nanoplasmonic structure than in bulk magnetic material [2]. The MO effects reveal themselves as a dependence of the structure's optical properties on the external magnetic field, and vice versa [3].

However, SPPs experience strong losses in metals. An employment of ferromagnetic dielectrics in nanoplasmonic structures leads to additional SPP damping in dielectric, that, in its turn, decreases the MO effect and a Q-factor of the magneto-plasmon resonance. Loss compensation and amplification of SPPs have been investigated deeply in active non-magnetic materials [4].

We address an enhancement of magneto-optical effects in plasmonic nanostructures with acive layer of doped ferromagnetic garnet. As a dopants we choose rear-earth or transition metals ions. The stimulated emission of dopants compensates the losses of SPP wave, and increases the Q-factor of magneto-plasmon (MP) resonance.

The bismuth-iron garnet (BIG) doped by ions, and covered by gold periodic structure is considered. A pump beam illuminates a dielectric from the substrate, and excites active centers in gain medium. The SPP excited by probe beam propagates along an interface of metal and doped ferromagnetic dielectric material. A stimulated emission of dopants enhances the SPP wave. We consider the BIG with two types of dopants, Yb and Nd ions. By numerical simulations an amplification of the transverse MO intensity effect in the considered nanostructures with gain is shown. For various values of the pain parameters the intensity of transmitted light changes slightly. However, the MO parameter excels high sensitivity and increases up to 1.5-fold rise in comparison with passive nanostructure.

The SPP amplification in plasmonic structures with garnets is demonstrated in experiment.

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Amplification of cross-polarization conversion of terahertz radiation by an active graphene metasurface

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It is known that an electromagnetic wave polarization conversion can take place only in systems that do not possess a plane of the mirror symmetry. Commonly, the DC magnetic field is applied to break the mirror symmetry and obtain terahertz (THz) wave polarization rotation in graphene [1]. In practical terms, this leads to substantial increase in the size and weight of THz polarization converters.

In this paper, the transformation of polarization of THz radiation by graphene metasurface formed by a periodic array of graphene nanoribbons located at the surface of a high-refractive-index dielectric substrate (Si in our case) in the absence of external DC magnetic field is studied theoretically. Mirror symmetry of the structure is broken for oblique incidence of THz wave (at incidence angle θ) when the direction of periodicity of the graphene nanoribbon comprise angle $\phi \neq 0$ with the plane of incidence of incoming THz wave.

The calculations were performed for realistic parameters of graphene at room temperature. Fig. 1 shows the variation of the polarization conversion coefficient, which is ratio between the power flux of the cross-polarized component in the reflected wave and the incident wave. The polarization conversion coefficient increases along the first-plasmon-resonance lobe from vanishingly small value for non-pumped graphene to giant value (more than 10^2) for pumped graphene around the plasmon self-excitation regime where the plasmon gain balances the total (dissipative plus radiative) losses in graphene [2]. The vicinity the self-excitation regime marked by dark red color in Fig. 1. It is shown that the amplified polarization conversion can be achieved in the total internal reflection (TIR) regime of THz wave from the graphene metasurface at room temperature.

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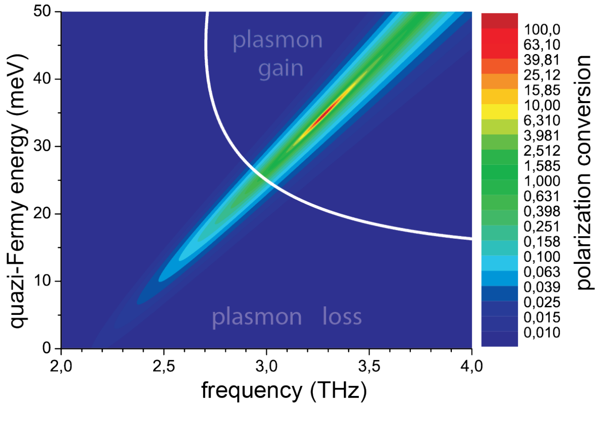

Fig. 1: Polarization conversion coefficient in the TIR regime of THz wave ($\theta = \phi = 45°$) at the fundamental plasmon resonance in the graphene nanoribbon array with period 800 nm and nanoribbon width 400 nm as a function of the quasi-Fermi energy and frequency for the electron relaxation time 10^{-12} s.

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Giant plasmon amplification in active graphene - hexagonal boron nitride heterostructures

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Graphene - hexagonal boron nitride (h-BN) van der Waals heterostructures give the possibility of plasmon propagation in graphene with a very low damping and a strong plasmonic field localization near graphene [1]. This possibility is partly caused by exact matching of the crystal structures of graphene and h-BN [2]. Hexagonal boron nitride is the material with the natural hyperbolic behavior [3], namely, its in - and out-of-plane components of permittivity tensor are opposite in signs in the reststrahlen frequency bands [4].

In this paper, we study the amplification of plasmons in active graphene (with the energy population inversion of free charge carries) on a h-BN substrate. We have numerically calculated the plasmon dispersion and plasmon gain in frequency region near the reststrahlen frequency band where h-BN exhibits hyperbolic behavior.

Graphene monolayer is deposited on the top surface ($y = 0$ in Fig. 1 (a)) of a semiinfinite substrate of h-BN. We plot in Fig. 1 (b) the dispersion of plasmons in graphene on h-BN substrate (solid curve)as compared with the dispersion of plasmons in graphene on SiC substrate (dashed curve). In the studied frequency range, SiC is isotropic material (with a scalar permittivity). Plasmon dispersion in graphene on h-BN substrate demonstrates an unusual behavior in the reststrahlen frequency band with the backward-wave branch unlike the dispersion of plasmons in graphene on SiC substrate. The power gain increment per the plasmon wavelength as a function of frequency is shown in Fig. 1 (c). One can see from Fig. 1 (c) that the power gain increment in graphene on h-BN substrate (solid curve) exceeds the same quantity in graphene on SiC substrate (dashed curve) an order of magnitude in the backward-wave frequency band (compare curves *1* and *2* in Fig. 1 (c)).

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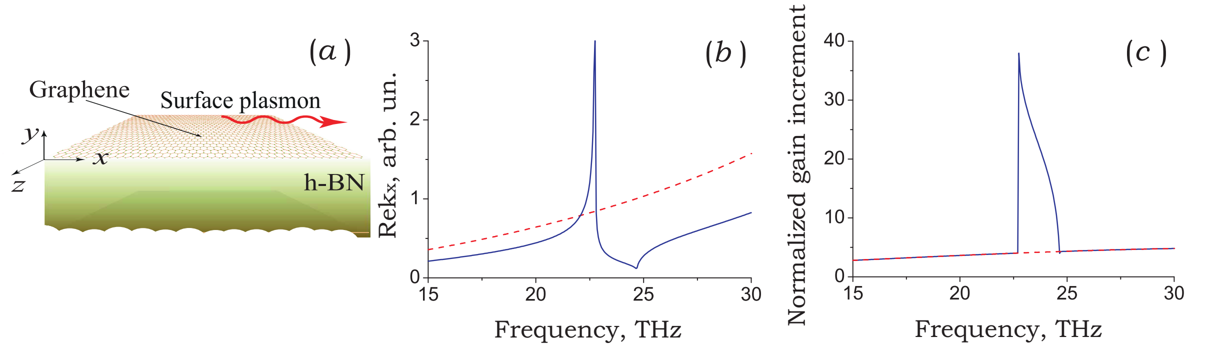

Fig. 1: (a) Schematic view of structure under consideration, (b) dispersion of plasmons (k_x denotes the x-component of the plasmon wavevector) and, (c) power gain increment per the plasmon wavelength as functions of frequency.

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Suitable equations for the description of transient regimes of the lasing in the surface plasmon lasers

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In laser physics, either Maxwell-Bloch equations or the rate equations are used for description of the interaction of electromagnetic field with atoms of the gain medium. Both of these equations are suitable for the description of stationary lasing in the lasers with high quality factor [1, 2]. Unfortunately, neither Maxwell-Bloch equations nor the rate equations are suitable for the description transient regimes of the lasing in the lasers with low quality factor, e.g., the surface plasmon lasers [3, 4, 5, 6, 7, 8, 9]. The Maxwell-Bloch equations are unsuitable for this purpose because they do not describe the process of a spontaneous emission. At the same time, the rate equations are unsuitable because they do not account finite value of the speed of light. In this work, we derive system of equations for the number of photons in the cavity modes, a population inversion of the atoms of the gain medium, a flow of energy between the atoms of the gain medium and the electromagnetic field, and the energy of interaction of the atoms of the gain medium with the electromagnetic field. We demonstrate that our system equations is suitable for the description transient regimes of the lasing in the surface plasmon laser.

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Light scattering control with reflective metasurfaces: from polarization control to random-phase scattering

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Recently, metasurfaces (the two-dimensional version of metamaterials) have been gaining increasing attention due to their remarkable abilities in light manipulation, versatility, ease of on-chip fabrication, and integration owing to their planar profiles. Many exotic phenomena and useful flat optical devices have been demonstrated, such as anomalous reflection/refraction, surface wave coupling and planar focusing lenses. Among all the different design approaches, the reflective metasurfaces (also known as gap-plasmon metasurfaces), which consists of a subwavelength thin dielectric spacer sandwiched between an optically thick metal film and an array of metal nano-antennas, has gained awareness from researchers working in practical any frequency regime as its realization only requires on step of lithography, yet with the possibility to fully control the amplitude, phase and even polarization of the reflected light. In this talk we report some of our recent research progress on light scattering control by using gap plasmon-based reflective metasurfaces, such as highly-directional half-wave plate [1] and truly random-phase metasurfaces [2].

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Symmetry approach to the dark modes metasurfaces

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Abstract. *We introduce new concepts of direct dark modes and electromagnetically induced transparency excitation that do not depend on hybridization mechanism related to near-field coupling between elements. This greatly relaxes fabrication constraints for the optical domain where such kind of resonances presenting sharp spectral are highly desirable for sensing applications.*

The concept of dark states, initially introduced in atomic physics, was borrowed and intensively developed during the last decades in the fields of photonics, plasmonics and metamaterials. The interest to the concept of dark states was driven mainly by the ability to obtain sharp spectral features with steep intensity variation, which are highly desirable for sensing applications. Despite the great variety of studied designs, most of them are based on the same principle. It consists in associating a superradiant element bearing an electric dipolar momentum and acting as a radiative or bright mode, with a subradiant element bearing an electric quadripolar or magnetic dipolar momentum and playing the role of the dark (or trapped) mode. The mode hybridization induced by a strong coupling between bright and dark elements leads to the opening of a narrow electromagnetically induced transparency (EIT) window inside the absorption band.

With a few exceptions, the origin of the EIT in such systems was attributed to the destructive Fano interference between a directly excited bright mode with an indirectly excited dark mode. However the last theoretical advances lead to revisit this commonly shared interpretation.

In particular it was evidenced that no dark mode excitation is necessary for the existence of Fano resonances. They can be described by the interference of bright modes only [1, 2]. The Fano interference of two modes with substantially different radiative strength results in a very weak EIT effect. The origin of this apparent contradiction stems from the fact that the eigenmodes of the coupled system can significantly differ from those of the individual elements, and in general they are not orthogonal. An obvious question arising is whether it is possible to achieve EIT in a more efficient manner, without making use of hybridization mechanism but rather through an interaction of initially bright resonant elements. The implementation of such a direct EIT excitation mechanism is highly desirable because the great sensitivity of mode hybridization to the variation of separation distance between elements yields the reliable fabrication of such kind of structures for sensing applications in the optical domain highly challenging.

To circumvent the issues related to the modes hybridization, we recently considered a different dark mode excitation mechanism based only on symmetry matching conditions [3]. We bring evidence that dark mode excitation is neither relying on hybridization mechanism nor interference effects, and is thus distinctly different from EIT.

In the present study we further extend this concept from the microwave to the optical domain and demonstrate its implementation for both the case of free space and guided wave light propagation configurations. Furthermore, we bring additional evidence that in its turn EIT also can also be achieved by using mechanisms different from hybridization.

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Metasurfaces for Magnetic Resonance Imaging

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We reveal that the unique properties of ultrathin metasurface resonators can improve dramatically magnetic resonance imaging (MRI) [1]. We place a metasurface formed by an array of metallic wires inside a scanner under the studied object and achieve a substantial enhancement of the radiofrequency magnetic field by means of subwavelength near-field manipulation with metasurface, also allowing to improve scanner sensitivity, signal-to-noise ratio, and image resolution.

The detail study of the different eigenmodes of the metasurface and its impact on the signal-to-noise ratio enhancement will be discussed.

Our proposal bridges a gap between the fundamental ideas of metamaterials and applications spanning the research fields from electromagnetic engineering to medical diagnostics: we show how a metasurface can boost the functionality of the magnetic resonance imaging devices that are widely available in hospitals and directly demonstrate a dramatic imaging enhancement for a commercial magnetic resonance scanner and a biological tissue sample [1].

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For notes