Session 1A2
Extraordinary Transmission: Theory and Experiments

Extraordinary Transmission for the "Wrong" Polarization

M. Navarro-Cía[1], M. Beruete[1], V. Lomakin[2], S. A. Kuznetsov[3], and M. Sorolla[1]

[1]Millimeter and Terahertz Waves Laboratory, Universidad Pública de Navarra, Spain
[2]Department of Electrical and Computer Engineering, University of California-San Diego, USA
[3]Novosibirsk State University, Budker Institute of Nuclear Physics SB RAS, Russia

Abstract— The phenomenon of strongly enhanced transmission through metal plates perforated with arrays of subwavelength holes led to an increased interest to the area of plasmonics [1, 2]. There is general consensus that the physical mechanism behind the enhanced transmission phenomena is a strong resonance caused by the excitation of a surface wave [3, 4], which becomes leaky through the interaction with the periodic structure. In the optical regime such leaky waves are typically associated with surface plasmon polariton, which are TM (p) polarized waves [3, 4]. However, other realizations of surface waves are possible in the optical as well as microwave and terahertz regimes.

One of less commonly known mechanisms is through the interaction with grounded slab modes, which can be of conventionally considered TM (p) polarization or of (anomalous) TE (s) polarization [4, 5]. Enhanced transmission of TE polarized waves is a clear manifestation of the underlying physics of the general leaky wave nature of the phenomenon. Recently, we reported measurements of TE transmission in the millimeter-wave [6, 7].

In this work, we present a complete analytical, numerical, and experimental study of the conditions for anomalous TE enhanced transmission. These results can find uses in interesting applications such as sensing in the THz regime.

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Anisotropy in Extraordinary Transmission Fishnet Structures

M. Navarro-Cía, M. Beruete, and M. Sorolla
Millimeter and Terahertz Waves Laboratory, Universidad Pública de Navarra, Spain

Abstract— After the first realization of a Negative Refractive Index Metamaterial (NIM) in the microwave regime [1], most research efforts were directed towards a NIM working at optical frequencies. To date, the most promising structure is the so-called fishnet structure, which consists in two perforated plates separated by a dielectric [2]. In parallel, other strategies to get negative refraction aside from the traditional combination of doubly negative metamaterials were investigated. It was found that with anisotropic media, called indefinite media, negative refraction was feasible [3].

Our contribution here was twofold: firstly, we could demonstrate that fishnet structures are equivalent to stacked Extraordinary Transmission [4, 5] hole arrays, extending the study to a stack larger than two plates and, besides, showed negative refraction in a prism of stacked hole arrays [6]. Secondly, we showed that this structure is strongly anisotropic and has complex two-dimensional dispersion diagram [7, 8] that can be analyzed with the theory of indefinite media of Ref. [3]. In Ref. [7], we reported intrinsic negative refraction in stacked hole arrays and in Ref. [8] extended the analysis for the two principal polarization states, with negative or positive refraction depending on the wave polarization.

In this work, we will analyze in depth the anisotropy characteristic of fishnet structures and will link it with the rich variety of refraction angles obtained with them. These results could be of interest both from a fundamental as well as practical point of view and could lead to interesting applications such as unconventional beam steerers.

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Extraordinary Transmission and Light Confinement in Subwavelength Metallic Films Apertures

R. Ortuño, C. García-Meca, F. J. Rodríguez-Fortuño, and A. Martínez
Nanophotonics Technology Center, Universidad Politécnica de Valencia, Spain

Abstract— Light-matter interactions in a metal layer patterned at the subwavelength scale give rise to a wide variety of optical resonances. Since the discovery of extraordinary light transmission, numerous experiments on such subwavelength apertures of opaque metallic films have demonstrated the ability to control light confinement and light propagation at the subwavelength scale.

The pattern in periodic structures allows coupling mechanisms between impinging light and surface plasmon waves. The excitation of horizontal coupled surface plasmons on the surfaces of the grating is pointed out to explain the extraordinary transmission of light trough periodic arrays of subwavelength apertures in metallic films. However, other mechanisms are also responsible for the high transmission and huge confinement of light in metallic gratings. For instance, waveguide modes, which appear in one-dimensional gratings made of narrow slits, also play an important role in the onset of extraordinary transmission. In addition, when the patterned metallic film is surrounded by a dielectric material, the excitation of cladding modes by the incoming light also cause extraordinary transmission resonances.

Moreover, cascading extraordinary transmission structures leads to a magnetic resonance response which yields a left-handed behavior and a negative refraction over a specific frequency range. By properly adjusting the separation distance among the cascaded metallic layers the negative refractive index can be extended over a larger frequency range.

These phenomena allow us to design planar optical elements having different refractive indices and spectral dispersion properties. This is very attractive for many optical applications in fundamental optics and in optoelectronics, like lenses and filters, and open up new possibilities in controlling and manipulating light by a wide range of plasmonic materials. In this sense, we have designed subwavelength structures for filtering purposes in the mid-infrared frequency range with high transmission levels. In addition, one advantage of such filters is their simple and compact implementation by comparison with conventional multilayer filters due to their huge number of layers and their large thicknesses required in the mid-infrared domain.

Transmission Properties of Dual-period Arrays of Cylinders

D. C. Skigin[1] and M. Lester[2]

[1]Applied Electromagnetics Group, Physics Dept., FCEN, University of Buenos Aires
and IFIBA (CONICET), Argentina
[2]Grupo Optica de Sólidos-Elfo, Instituto de Física Arroyo Seco, Facultad de Ciencias Exactas
Universidad Nacional del Centro de la Provincia de Buenos Aires, Argentina

Abstract— We investigate the potential of dual-period structures to control and manipulate the transmitted intensity. We consider supergratings (periodic arrays with a compound unit cell) in which each period comprises several cylinders with circular cross section.

Three different configurations are considered: (i) all the cylinder axes are contained in the same plane; (ii) the cylinder axes in each unit cell are aligned in a plane which is tilted with respect to the periodicity direction; (iii) evanescent wave illumination.

For case (i) we show that this kind of structure permits one to control the diffracted response, regardless of the cylinder material and the incident polarization. A given diffraction order can either be enhanced or suppressed by appropriately choosing the geometrical parameters of the structure. Our numerical results suggest that the effect produced by wire gratings with dual-period characteristics is basically a geometric effect, and it can be present for other shapes of individual scatterers within each subarray. If the cylinder diameters are much smaller than the incident wavelength (subwavelength cylinders), and their axes are aligned in a plane tilted with respect to the periodicity direction (case (ii)), this structure behaves like a blazed grating in the sense of its capability to enhance the intensity in a pre-designed direction. This blazed-like behavior is found for both incident polarization modes, and for dielectric as well as for metallic cylinders. We also consider dual-period arrays illuminated by an evanescent wave generated by total internal reflection in a close interface. For particular wavelengths, the system exhibits resonances and the inhomogeneous wave is converted into propagating waves that radiate to the far field. This effect can be controlled by varying the geometrical parameters of the structure, such as the period and the inclination angle. Therefore, the transmitted intensity can be sent to a predesigned direction. If we consider the quick evolution of manufacturing techniques of nanogratings, such structures constitute a realizable alternative not only for the microwave and millimeter wave regions but also for optical devices, and they could be used in highly sensitive detection devices, among other applications.

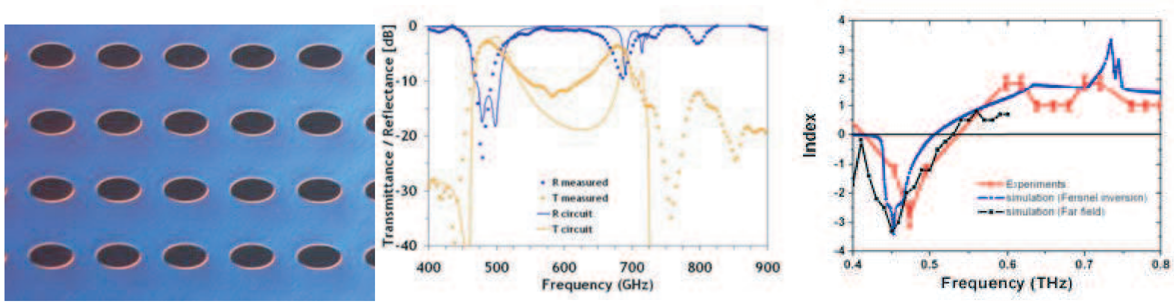
Bulk Metamaterial under Front Illumination at Terahertz Frequencies

J. Carbonell[1], **S. Wang**[2], **E. Lheurette**[2], **and D. Lippens**[2]

[1]Wave Phenomena Group, Departamento de Ingeniería Electrónica
Universidad Politécnica de Valencia, Camino de Vera, s/n, E-46022 Valencia, Spain
[2]IEMN, Université des Sciences et Technologies de Lille
Av. Poincaré B.P. 60069, 59652 Villeneuve d'Ascq Cedex, France

Abstract— Front side illuminated devices operating at terahertz and even higher frequencies have become a very active field of research owing to their wide range of possible applications. In particular, devices exhibiting a negative refractive index may open the path to obtain high-resolution lenses, super scatters, and other challenging purposes. Several routes have been explored to fulfill a normal incidence requirement such as the ones based on the so-called nanorod or fishnet approaches. Nevertheless, the Terahertz spectral range still raises some issues. The first and perhaps the most important difficulty stems from the requirement of generating (virtually or de facto) of a resonant current loop, as in the generic so-called split ring resonator technology. This loop will induce an artificial magnetic moment under grazing incidence. This key issue explains why most of the present works in the Terahertz frequency range have addressed preferably metasurfaces based on resonant electrical dipoles rather than bulk metamaterials. Clearly the scaling of the underlying concept for artificial magnetism from microwaves to Terahertz frequencies requires developing other excitation techniques under front side illumination. The so-called sub-wavelength holes array and fishnet technologies are two suitable routes towards this goal. Recent demonstrations of left-handedness at millimeter, sub-millimeter wavelengths and in the infrared spectral region have been proposed.

We have investigated several bulk metamaterial prototypes under front illumination at Terahertz frequencies [1, 2]. To this aim we have fabricated several stacked structures of slab- and wedge-types. The devices are constituted of holes arrays etched in gold thin films, which are stacked according to a sequential mask with benzocyclobutene (BCB) spacer polymers. We have characterized them with a measurement setup based on angle-resolved time domain spectroscopy (TDS) carried out at operating frequencies around 0.5 THz. Analysis of these experimental data is carried out in conjunction with numerical simulations, effective parameters retrieval methods and equivalent circuit analysis. In terms of the experimental results, a favorable comparison can be established with a broad-band equivalent circuit. Also, the dispersion of refractive index retrieved from the Snell law on these measured data shows comparable trends with the dispersion deduced from numerical simulations. Complex transmission and reflection measurements we have performed on slab- and wedge-type samples permit to confirm the findings regarding the effective retrieved parameters.



(a) (b) (c)

Figure 1: (a) Optical microscope view of the surface of a fabricated prototype, (b) transmittance and reflectance for a five layer stacked structure in magnitude (equivalent circuit response compared to measured data), and (c) frequency dependence of effective refractive index extracted for a 10-layer wedge type device (far field).

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Holey Structured Metamaterials

Francisco J. Garcia-Vidal
Departamento de Física Teórica de la Materia Condensada (C-05), Facultad de Ciencias
Universidad Autónoma de Madrid, Spain

Abstract— The interest in the optical properties of metallic films perforated with periodic arrays of subwavelength holes was revitalized after the discovery of the phenomenon of extraordinary optical transmission (EOT), reported by Ebbesen and co-workers in 1998 [1, 2]. This phenomenon is characterized by the emergence of some transmission resonances that appear at wavelengths slightly larger than the period of the array. It is now well-established that the origin of this intriguing behaviour is associated with the excitation of surface plasmon polaritons (SPPs) by the incident light. Here in this summary, we will demonstrate how a single holey metal film (or several holey metal films stacked together) can present interesting optical and acoustic properties when it behaves as a metamaterial, i.e., in the effective medium limit in which the operating wavelength is much larger than the size of the holes and period of the array.

The concept of spoof surface plasmon was firstly introduced in 2004 by Pendry, Martin-Moreno and Garcia-Vidal [3]. In that paper, it was demonstrated how the optical response of a holey perfect conductor can be effectively mapped into a Drude-like formula in which the plasma frequency of the real metal is replaced by the cutoff frequency of the hole waveguide. The first theoretical studies on the concept of spoof surface plasmons were done for planar geometries [3, 4], i.e., periodic arrays of holes and periodic arrays of dimples. Experimental verification of this concept was firstly reported in the microwave regime by Hibbins and co-workers by looking at the angle-dependent transmission spectrum through periodic arrays of holes [5]. Very recently, the subwavelength (vertical) confinement of these geometrically induced surface electromagnetic modes was verified in the terahertz regime [6].

Recently, Zhang and co-workers [7] have proposed and demonstrated a negative index metamaterial working at near infrared frequencies with a design very similar to the structure showing EOT. This metamaterial is composed by a two-dimensional array of holes penetrating completely in a metal-dielectric-metal film stack. This double-fishnet (DF) structure has received a lot of attention for its negative refractive index (NRI) at visible and near infrared frequencies. A theory is presented of the negative refractive index observed in the double-fishnet structures [8]. We find that the electrical response of these structures is dominated by the cutoff frequency of the hole waveguide whereas the resonant magnetic response is due to the excitation of gap surface plasmon polaritons propagating along the dielectric slab. Associated with this origin, we will show how the negative refractive index in these metamaterials presents strong dispersion with the parallel momentum of the incident light.

We will also analyze the distinct behaviour observed for acoustic waves [9]. We will show how the physics of the acoustic double-fishnet is quite different to its electromagnetic counterpart. This metamaterial structure exhibits a tuneable attenuation band but does not present negative-index behaviour. The blockage of acoustic radiation originates from a negative effective bulk modulus, associated with the excitation of a gap mode in the region between the two holey plates. Importantly and as a difference with the electromagnetic case, the acoustic gap mode presents a weak dispersion with parallel momentum and its bandwidth can be tuned at will by varying the thickness of the separating layer.

Finally we will analyze possible superlensing effects in holey metal films. We will show that within the effective-medium limit and at some resonant frequencies, holey perfect conductor films make perfect endoscopes, i.e., are capable of transforming an image from the input to the output surface of the film with very deep subwavelength resolution [10]. To corroborate our finding in a realistic structure, a full numerical calculation including diffraction and losses is presented for a one-dimensional perforated metal film in the terahertz regime. However, the practical implementation of these endoscopes for three-dimensional objects using a two-dimensional array of holes instead of a one-dimensional array of slits is limited due to the existence of a cutoff wavelength inside the holes. Importantly, this limitation is lifted in the case of acoustic waves. We have recently demonstrated a three-dimensional holey structured metamaterial that achieves acoustic imaging down to a feature size of $\lambda/50$ [11]. The evanescent field components of a subwavelength object are efficiently transmitted through the structure thanks to their strong coupling with Fabry-Perot resonances inside the holey plate. This capability of acoustic imaging at a very deep subwavelength scale brings promising perspectives for broad applications in medical ultrasonography, underwater sonar and ultrasonic non-destructive evaluation.

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Anomalous Band Formation in Terahertz Nanoresonators

J. Bravo-Abad[1], L. Martin-Moreno[2], F. J. Garcia-Vidal[1], Y. M. Park[3], H. R. Park[3], K. J. Ahn[3], H. S. Kim[3], Y. H. Ahn[4], and D.-S. Kim[3]

[1]Departamento de Fisica Teorica de la Materia Condensada
Universidad Autonoma de Madrid, E-28049 Madrid, Spain
[2]Instituto de Ciencia de Materiales de Aragon (ICMA)
Departamento de Fisica de la Materia Condensada, CSIC-Universidad de Zaragoza
E-50009 Zaragoza, Spain
[3]Center for Subwavelength Optics, Department of Physics and Astronomy
Seoul National University, Seoul 151-747, Korea
[4]Division of Energy Systems Research, Ajou University, Suwon 433-749, Korea

Abstract— Light transmission through subwavelength apertures in metal films has been extensively studied since the phenomenon of Extraordinary Optical Transmission was reported over a decade ago [1]. In this context, it was shown that the collective response of an array of subwavelength holes perforated in a metallic screen is strongly influenced by the shape of the apertures forming the array [2]. It was also found that this strong dependence is already present in a single isolated hole [3, 4]. In particular, cutoff transmission resonances were reported in single rectangular holes, which enable dramatic enhancements of the corresponding normalized-to-area transmission just by increasing the ratio between the long and short sides of the aperture.

In this talk, we describe our recent analysis of band formation in periodic arrays of rectangular holes [5]. Specifically, we consider one-dimensional arrays formed by rectangular apertures tailored to work as resonators in the THz frequency regime, each aperture being characterized by nanoscale width but a length of a hundred microns. First, we present THz time-domain spectroscopy measurements of the transmission amplitude through this class of systems. From these measurements two unexpected observations emerge: on one hand, in contrast to what it is expected from a canonical tight-binding picture of band formation in periodic systems, the linewidth and the position of the resonant peak observed in the transmission spectra do not show a monotonic behavior as the period of the array is changed. On the other hand, the maximum normalized-to-area transmitted amplitude decreases as more apertures are added to the sample.

In the second part of this talk, we discuss the physical origin of these findings in terms of both numerical calculations based on a theoretical coupled-mode formalism and a minimal model that captures the main features observed experimentally. Thus, we show in detail how the considered array of coupled THz nanoresonators displays unique features stemming from both the oscillating behavior of the electromagnetic coupling between holes and its long-range character.

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Analytical Modeling of Extraordinary Transmission in the Presence of Dielectric Slabs

R. Rodríguez-Berral[1], **F. Medina**[2], **and F. Mesa**[1]

[1]Microwaves Group, Department of Applied Physics 1, University of Seville, Spain
[2]Microwaves Group, Department of Electronics and Electromagnetism, University of Seville, Spain

Abstract— The phenomenon of extraordinary transmission of electromagnetic waves through electrically small apertures is nowadays well understood and several authorative reviews are available [1–4]. The basic idea is that surface waves can be strongly excited over the structured surface (surface plasmon polaritons, SPP) at some critical frequencies close to the onset of the first diffraction order of the grating. Although the plasma behavior of metals at optical frequencies influences the detailed shape of the transmission spectrum, it is the periodic distribution of holes or slits the main cause behind the phenomenon. The analysis of this type of structures can be reduced to the study of a single unit cell [5]. Moreover, the analysis of this unit cell straightforwardly leads to reduced order circuit models such as those reported in [6] and [7] to deal with 2D arrays of holes and 1D simple/compound slit gratings respectively. However, most of the structures studied in the previous references are free standing metallic surfaces. The presence of dielectric slabs on which the metal structure is deposited or printed is essential due to fabrication requirements. From the point of view of SPP theory, it is more or less obvious that the transmission spectrum is expected to experience important modifications with respect to the free-standing holey metal screen: The presence of dielectric slabs adds new opportunities to surface waves to propagate along the structure. The consequences of adding dielectric slabs to the holey metallic surface has been explored by several authors [8–10]. These authors make use of different approaches but emphasis is given to the role of the surface waves. The aim of the present work is to show how the impedance matching point of view adopted in [6, 7] can be extended to deal with slit–like dielectric coated metallic perforated stuctures. This approach provides an alternative explanation to the appearence of new peaks and dips in the transmission spectrum (with respect to the free–standing structure). The behavior of these systems, under certain restrictions, can be modeled using a few circuit parameters, which are enough to describe the transmission and reflection spectra over a very wide frequency band.

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Enhanced Transmission through Deep Subwavelength Apertures Using Metamaterials

Ekmel Ozbay
Nanotechnology Research Center, Bilkent University, Bilkent, Ankara 06800, Turkey

Abstract— We obtained enhanced transmission of electromagnetic waves through a single subwavelength aperture by making use of the resonance behavior of a split ring resonator (SRR) at microwave frequencies. By placing a single SRR at the near-field of the aperture, strongly localized electromagnetic fields were effectively coupled to the aperture with a radius that is twenty times smaller than the resonance wavelength ($r/\lambda = 0.05$). We obtained 740-fold transmission enhancement by exciting the electric resonance of SRR. We have recently extended this transmission enhancement performance to even higher values. The respective design parameters of the connected SRRs (Sample A&B) are depicted in Fig. 1(a). We have demonstrated the extraordinary transmission by using these samples. Fig. 1 illustrates how we incorporate the samples with the aperture. We drilled an opening on a large metal plate of $1\,\mathrm{m} \times 1\,\mathrm{m}$. The opening on our metal screen constituted the subwavelength aperture. The area of the subwavelength aperture is $3 \times 7.5\,\mathrm{mm}^2$ (width × height). The connected SRRs are inserted inside the aperture. Transmission measurements were performed with conventional horn antennas operating around the frequency band of our interest. The antennas were located 8 cm away from each other and the metal plate was positioned in between these antennas.

The enhancement results are calculated by dividing the transmission values obtained from the apertures with the samples to the only aperture case for every frequency. The measured transmission results are portrayed in Fig. 2(a) and Fig. 2(d) in linear scale. The peaks are the evidence of the transmission enhancement in the presence of the samples. Single aperture transmission results were multiplied with 10 to be able to visualize both results on the same graph. Likewise, Fig. 2(b) and Fig. 2(e) depict the simulation results. The simulation results agree well with the experimental results. The enhancement peaks are spotted at similar frequencies. The minor discrepancies are due to the difficulty of the exact manual alignment of the samples in the experiments as well as the small variations in the manufacturing processes and the crude modeling of the materials used in the experiments. Finally, the measured enhancement figures are plotted in Figs. 2(c) and (f). We experimentally observed a more than 70,000 times transmission enhancement for Sample A, whereas a higher than 5,300-fold transmission improvement was achieved with Sample B.

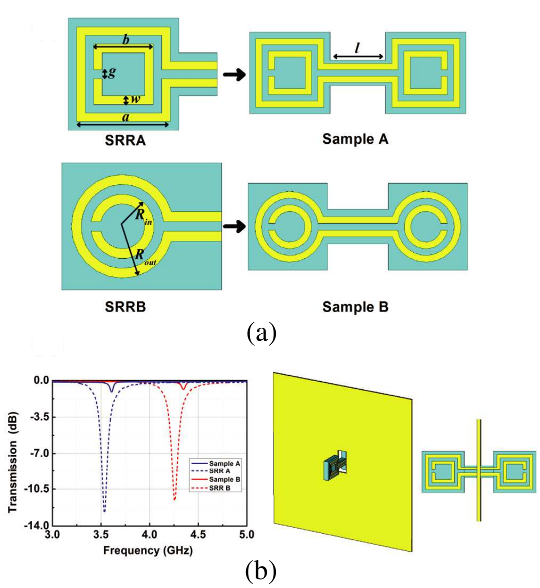

Figure 1.

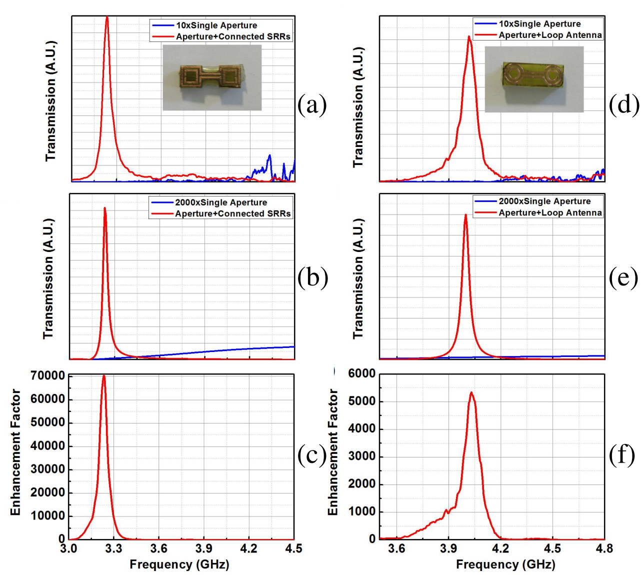

Figure 2.

Extraordinary Kerr Effect in Transmission in Magnetoplasmonic Nanostructured Films

V. I. Belotelov[1,2], **I. A. Akimov**[3], **M. Pohl**[3], **V. A. Kotov**[1,4], **A. S. Vengurlekar**[5], **A. V. Gopal**[5], **D. Yakovlev**[3], **A. K. Zvezdin**[1], **and M. Bayer**[4]

[1]A. M. Prokhorov General Physics Institute RAS, Moscow 119991, Russia
[2]M. V. Lomonosov Moscow State University, Moscow 119992, Russia
[3]Dortmund University, Dortmund 44221, Germany
[4]V. A. Kotelnikov Institute of Radio Engineering and Electronics RAS, Moscow 125009, Russia
[5]Tata Institute of Fundamental Research, Mumbai 400005, India

Abstract— Nowadays, much effort is being made in the area of nanophotonics, which demands materials with outstanding optical performance and tunability at the femtosecond time scale. For these purposes, magnetooptical materials hold great potential since their optical properties can be easily altered via magnetic field. However, the magnetooptical effects are usually not sufficiently strong. Until recently, the streamline in the magnetooptical effects enhancement was on chemical side. In this paper we propose a new concept. It was revealed recently that surface plasmons lie at the root of the extraordinary optical transmission phenomenon in the metallic films periodically perforated with subwavelength hole or slit arrays. Surface plasmons also remain decisive in the proposed here nanoscale magnetooptical material. In this material a thin magnetic dielectric film is attached to the perforated metal, thus constituting a kind of metal-dielectric heterostructure with nanoscaled pattern. Unique features of the proposed material are high value of the magnetooptical constant and low optical losses. We demonstrate experimentally a significantly enhanced the transverse Kerr effect in transmitted light. Observation of this effect in transmission in smooth ferromagnets is extremely difficult because of its small value and/or ultra low detected light intensity. The new magnetoplasmonic material allowed to make the effect several orders larger and to observe it near the extraordinary transmission peaks. Furthermore, the effect is very sensitive to the properties of the surface plasmons and is shown to be an efficient method for in-depth studies of plasmonic systems. The other magnetooptical effects can be also enhanced by the same structure. It is possible to switch among the effects by applying magnetic field in different directions. It is of great importance for applications in the fields of telecommunication, computing and sensing.