Advanced fabrication of hyperbolic metamaterials

Hyperbolic metamaterials can provide unprecedented properties in accommodation of high-k (high wave vector) waves and enhancement of the optical density of states. To reach such performance the metamaterials have to be fabricated with as small imperfections as possible. Here we report on our advances in two approaches in fabrication of optical metamaterials. We deposit ultrathin ultrasmooth gold layers with the assistance of organic material (APTMS) adhesion layer. The technology supports the stacking of such layers in a multiperiod construction with alumina spacers between gold films, which is expected to exhibit hyperbolic properties in the visible range. As the second approach we apply the atomic layer deposition technique to arrange vertical alignment of layers or pillars of heavily doped ZnO or TiN, which enables us to produce hyperbolic metamaterials for the near- and mid-infrared ranges.
Broadband infrared absorption enhancement by electroless-deposited silver nanoparticles

Decorating semiconductor surfaces with plasmonic nanoparticles (NPs) is considered a viable solution for enhancing the absorptive properties of photovoltaic and photodetecting devices. We propose to deposit silver NPs on top of a semiconductor wafer by a cheap and fast electroless plating technique. Optical characterization confirms that the random array of electroless-deposited NPs improves absorption by up to 20% in a broadband of near-infrared frequencies from the bandgap edge to 2000 nm. Due to the small filling fraction of particles, the reflection in the visible range is practically unchanged, which points to the possible applications of such deposition method for harvesting photons in nanophotonics and photovoltaics. The broadband absorption is a consequence of the resonant behavior of particles with different shapes and sizes, which strongly localize the incident light at the interface of a high-index semiconductor substrate. Our hypothesis is substantiated by examining the plasmonic response of the electroless-deposited NPs using both electron energy loss spectroscopy and numerical calculations.
SNOM, near-field microscopy, anapole, multipole decomposition, all-dielectric nanoparticles
Effect of substrate on optical bound states in the continuum in 1D photonic structures

Optical bound states in the continuum (BIC) are localized states with energy lying above the light line and having infinite lifetime. Any losses taking place in real systems result in transformation of the bound states into resonant states with finite lifetime. In this work, we analyze properties of BIC in CMOS-compatible one-dimensional photonic structure based on silicon-on-insulator wafer at telecommunication wavelengths, where the absorption of silicon is negligible. We reveal that a high-index substrate could destroy both off-Γ BIC and in-plane symmetry protected at-Γ BIC turning them into resonant states due to leakage into the diffraction channels opening in the substrate.
High-Quality Ultrathin Gold Layers with an APTMS Adhesion for Optimal Performance of Surface Plasmon Polariton-Based Devices

A low-absorption adhesion layer plays a crucial role for both localized and propagating surface plasmons when ultrathin gold is used. To date, the most popular adhesion layers are metallic, namely, Cr and Ti. However, to the best of our knowledge, the influence of these adhesion layers on the behavior of propagating plasmon modes has not been thoroughly investigated nor reported in the literature. It is therefore important to study the effect of these few- to several-nanometers-thick adhesion layers on the propagating plasmons because it may affect the performance of plasmonic devices, in particular, when the Au layer is not much thicker than the adhesion layers. We experimentally compared the performances of the ultrathin gold films to show the pivotal influence of adhesion layers on highly confined propagating plasmonic modes, using Cr and 3-aminopropyl trimethoxysilane (APTMS) adhesion layers and without any adhesion layer. We show that the gold films with the APTMS adhesion layer have the lowest surface roughness and the short-range surface plasmon polaritons supported on the Au surface exhibit properties close to the theoretical calculations, considering an ideal gold film.

General information
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Laguerre-Gauss beam generation in IR and UV by subwavelength surface-relief gratings

The angular momentum of light can be described by the states of spin angular momentum, associated with polarization, and orbital angular momentum, related to the helical structure of the wave front. Laguerre-Gaussian beams carry orbital angular momentum and their generation can be done by using an optical device known as q-plate. However, due to the usage of liquid crystals, these components may be restricted to operate in specific wavelengths and low power sources. Here we present the fabrication and characterization of q-plates made without liquid crystals, using processes of e-beam lithography, atomic layer depositions and dry etch techniques. We exploit the phenomenon of form birefringence to give rise to the spin-to-orbital angular momentum conversion. We demonstrate that these plates can generate beams with high quality for the UV and IR range, allowing them to interact with high power laser sources or inside laser cavities.
Midinfrared Surface Waves on a High Aspect Ratio Nanotrench Platform

Optical surface waves, highly localized modes bound to the surface of media, enable manipulation of light at nanoscale, thus impacting a wide range of areas in nanoscience. By applying metamaterials, artificially designed optical materials, as contacting media at the interface, we can significantly ameliorate surface wave propagation and even generate new types of waves. Here, we demonstrate that high aspect ratio (1:20) grating structures with plasmonic lamellas in deep nanoscale trenches, whose pitch is 1/10 – 1/35 of a wavelength, function as a versatile platform supporting both surface and guided bulk infrared waves. The surface waves exhibit a unique combination of properties: directionality, broadband existence (from 4 µm to at least 14 µm and beyond) and high localization, making them an attractive tool for effective control of light in an extended range of infrared frequencies.

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Optimizing sensitivity of Unmanned Aerial System optical sensors for low zenith angles and cloudy conditions

Satellite-based imagery in optical domains cannot provide information on the land surface during periods of cloud cover. This issue is especially relevant for high latitudes where overcast days and low solar zenith angles are common. Current remote sensing-based models of evapotranspiration or carbon assimilation are biased towards clear sky conditions, lacking important information on biophysical processes under cloudy conditions. Unmanned Aerial Vehicle (UAV) imagery has great potential to monitor and understand surface fluxes under cloudy conditions. For instance, in Denmark 73.54% of all days are non-clear (fraction of direct radiation less than 50%). UAV multispectral imagery acquired in these conditions tends to present low brightness and dynamic ranges, and high noise levels. Another problem is the influence of land cover types on the signal. For instance, over vegetated areas, even with low irradiance, saturation is reached in the near Infrared, while visible channels have low brightness. An individual camera setting for each channel and light conditions can improve sensor sensitivity while preventing saturation. This study aims to optimize the settings and radiometric corrections of a multispectral camera to produce high quality UAV imagery under low but homogeneous irradiance conditions. Laboratory experiments were conducted to link irradiance levels to different camera settings and calibration procedures. Results were tested outdoors over homogeneous and vegetated surfaces.

The multispectral camera (Tetra Mini-MCA6) has 6 channels in the visible and near Infrared. For the laboratory calibration experiment, different camera settings and typical irradiance levels from cloudy to clear sky were designed. The light-source is based on super-continuum generation to produce a continuous solar spectrum. It allows more flexible settings in illumination levels than tungsten halogen lamps. A Li-Cor 1800 integrating sphere and an ASD spectroradiometer (FieldSpec HandHeld 2) were also used. Images were acquired under varying integration time and illumination levels from 0.005 to 0.2 W·m⁻²·nm⁻¹·sr⁻¹. Two radiometric calibration methods were applied to find gains to convert digital numbers (DN) into radiance and also to correct vignetting effects, apparent as the fall-off pixel intensity from the image center towards edges. The first is to apply a pixel-wise calibration from DN to radiance. The second performs a vignetting correction based on distance from each pixel to the highest DN pixel and then a global image calibration of averaged DN to radiance. To test calibration performance, images were acquired outdoors over (i) homogeneous targets (Teflon panels, grass and soil plots) and (ii) with UAV flight campaigns over a willow eddy covariance flux site under different cloudiness levels and solar zenith angles using varying camera settings. Radiance, reflectance, and vegetation indices were validated with ASD measurements and signal to noise metrics and dynamic ranges were assessed. Our results indicate that the spectral gains and camera settings can be tuned to allow higher signal to noise ratio and optimize the sensor sensitivity. This maximizes the image radiometric resolution and prevents sensor saturation for each channel. This paper is a step forward for UAV campaigns using optical cameras for low zenith angles and/or cloudy conditions.

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Organisations: Department of Environmental Engineering, Water Resources Engineering, Department of Photonics Engineering, Diode Lasers and LED Systems, Plasmonics and Metamaterials, DTU Danchip, National Space Institute, Geodesy, Atmospheric Environment, European Commission - Joint Research Center
Transition from Optical Bound States in the Continuum to Leaky Resonances: Role of Substrate and Roughness

Optical bound states in the continuum (BIC) are localized states with energy lying above the light line and having infinite lifetime. Any losses taking place in real systems result in transformation of the bound states into resonant states with finite lifetime. In this Letter, we analyze properties of BIC in CMOS-compatible one-dimensional photonic structure based on silicon-on-insulator wafer at telecommunication wavelengths, where the absorption of silicon is negligible. We reveal that a high-index substrate could destroy both off-Γ BIC and in-plane symmetry protected at-Γ BIC turning them into resonant states due to leakage into the diffraction channels opening in the substrate. We show how two concurrent loss mechanisms, scattering due to surface roughness and leakage into substrate, contribute to the suppression of the resonance lifetime and specify the condition when one of the mechanisms becomes dominant. The obtained results provide useful guidelines for practical implementations of structures supporting optical bound states in the continuum.

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Reconfigurable thz polarizer
The present invention provides a polarizer. The polarizer comprises a first membrane having a first polarization region comprising a first plurality of membrane perforations; a second membrane having a second polarization region comprising a second plurality of membrane perforations; and a support structure to which the first and second membranes are attached, the support structure allowing a relative movement of the first membrane with respect to the second membrane,
the relative movement enabling an at least partial overlap of one or more membrane perforations in the first plurality of perforations with one or more membrane perforations in the second plurality of perforations in a direction normal to the first polarization region or normal to the second polarization region, resulting in corresponding one or more openings in said direction.

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Conductive Oxides Trench Structures as Hyperbolic Metamaterials in Mid-infrared Range
Nanostructures that possess hyperbolic iso-frequency contours exhibit unique properties of high anisotropy and extremely large wavevectors, which are the key issue to numerous photonic applications from subdiffraction imaging and superlens to sensing and spontaneous emission enhancement [1,2]. Moreover plasmonics for mid-infrared offer unique applications such as bio-sensing, thermal imaging and quest for novel materials and structures has been continuing [3]. In this report we show that vertical trench structures made of, for example, aluminum-doped ZnO (AZO) or other transparent conductive oxides can function as hyperbolic metamaterials (HMMs) for the mid-infrared wavelength region. We fabricated a probe sample by a combination of atomic layer deposition (ALD) and dry etch techniques. We templated a Si wafer with deep UV photolithography and made trenches by deep reactive ion etching. Subsequent deposition of an AZO layer by the ALD technique forms vertical AZO trenches with a high aspect ratio (Fig.1a). After homogenization procedure the structure exhibits hyperbolic dispersion (Fig.1b) serving as an attractive platform for light manipulation [4]. Characterization results will be reported at the conference.

Design, fabrication and SNOM investigation of plasmonic devices
Surface plasmon-polaritons are a possible solution for on-chip transportation and manipulation of information. Although there are several possibilities for designing the plasmonic waveguides, the two major caveats for all of them are the coupling to/from external sources and the losses they exhibit. In this work we will present an overview of our simulation, fabrication and characterisation activity in the plasmonic field where we tackle these issues. We start with presenting an optimised nanoantenna for coupling of free-propagating waves into a subwavelength slot waveguide modes. Optimised antennae show an increase in coupling efficiency up to 185 times compared to a bare waveguide. Once optimized, the nanoantennae were fabricated and the propagation in the slot waveguides was characterised. The characterisation shows an increase in the effective area (proportional to the coupling efficiency) of up to 175 times, similar to the calculated...
optimised parameters. We then move our attention to effective tapering of the plasmonic modes such that to achieve either strong field enhancement or propagation into thin plasmonic nanowires. Using on-chip nanofocusing with impedance-matched nanoantenna we can obtain a field enhancement of up to ~ 12000 evenly distributed in a volume of ~ 30x 30 x 10 nm3. The same taper can be used also for modifying the waveguide profile from a wide strip waveguide to a nanorod waveguide showing both the flexibility of our taper design as well as allowing to measure and compare the propagation characteristics in waveguides with various widths. We show that the propagation length matches very well the theoretical one and also obtain a limit for confinement of the mode in this type of plasmonic waveguides of ~ λ/15.

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Effective medium approximation for deeply subwavelength all-dielectric multilayers: when does it break down?
We report on theoretical analysis and experimental validation of the applicability of the effective medium approximation to deeply subwavelength (period λ/30) all-dielectric multilayer structures. Following the theoretical prediction of the anomalous breakdown of the effective medium approximation [H. H. Sheinfux et al., Phys. Rev. Lett. 113, 243901 (2014)] we thoroughly elaborate on regimes, when an actual multilayer stack exhibits significantly different properties compared to its homogenized model. Our findings are fully confirmed in the first direct experimental demonstration of the breakdown effect. Multilayer stacks are composed of alternating alumina and titania layers fabricated using atomic layer deposition. For light incident on such multilayers at angles near the total internal reflection, we observe pronounced differences in the reflectance spectra (up to 0.5) for structures with different layers ordering and different but still deeply subwavelength thicknesses. Such big reflectance difference values resulted from the special geometrical configuration with an additional resonator layer underneath the multilayers employed for the enhancement of the effect. Our results are important for the development of new homogenization approaches for metamaterials, high-precision multilayer ellipsometry methods and in a broad range of sensing applications.

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Fabrication of deep-profile Al-doped ZnO one- and two-dimensional lattices as plasmonic elements

In this work, we report on fabrication of deep-profile one- and two-dimensional lattices made from Al-doped ZnO (AZO). AZO is considered as an alternative plasmonic material having the real part of the permittivity negative in the near infrared range. The exact position of the plasma frequency of AZO is doping concentration dependent, allowing for tuning possibilities. In addition, the thickness of the AZO film also affects its material properties. Physical vapor deposition techniques typically applied for AZO coating do not enable deep profiling of a plasmonic structure. Using the atomic layer deposition technique, a highly conformal deposition method, allows us to fabricate high-aspect ratio structures such as one-dimensional lattices with a period of 400 nm and size of the lamina of 200 nm in width and 3 µm in depth. Thus, our structures have an aspect ratio of 1:15 and are homogeneous on areas of 2x2 cm² and more. We also produce two-dimensional arrays of circular nanopillars with similar dimensions. Instead of nanopillars, hollow tubes with a wall thickness on demand from 20 nm up to a complete fill can be fabricated.

Hyperbolic Metamaterials with Complex Geometry

We investigate new geometries of hyperbolic metamaterials such as highly corrugated structures, nanoparticle monolayer assemblies, super-structured or vertically arranged multilayers and nanopillars. All structures retain basic properties of hyperbolic metamaterials, but have functionality improved on particular purpose: increased absorption, radiative rate engineering, and selective control over volume plasmon-polaritons or directional surface waves.
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Lifetime of Nano-Structured Black Silicon for Photovoltaic Applications
In this work, we present recent results of lifetime optimization for nano-structured black silicon and its photovoltaic applications. Black silicon nano-structures provide significant reduction of silicon surface reflection due to highly corrugated nanostructures with excellent light trapping properties. We applied reactive ion etching technology at -20°C to create nano-structures on silicon samples and obtained an average reflectance below 0.5%. For passivation purposes, we used 37 nm ALD Al2O3 films. Lifetime measurements resulted in 1220 µs and to 4170 µs for p- and n-type CZ silicon wafers, respectively. This is promising for use of black silicon RIE nano-structuring in a solar cell process flow

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Near-field characterization of bound plasmonic modes in metal strip waveguides
Propagation of bound plasmon-polariton modes along 30-nm-thin gold strips on a silica substrate at the free-space wavelength of 1500 nm is investigated both theoretically and experimentally when decreasing the strip width from 1500 nm down to the aspect-ratio limited width of 30 nm, which ensures deep subwavelength mode confinement. The main mode characteristics (effective mode index, propagation length, and mode profile) are determined from the experimental amplitude-and phase-resolved near-field images for various strip widths (from 30 to 1500 nm), and compared to numerical simulations. The mode supported by the narrowest strip is found to be laterally confined within similar to 100 nm at the air side, indicating that the realistic limit for radiation nanofocusing in air using tapered metal strips is lambda/15. (C) 2016 Optical Society of America

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Nonlinear effects in propagation of long-range surface plasmon polaritons in gold strip waveguides
This paper is devoted to experimental and theoretical studies of nonlinear propagation of a long-range surface plasmon polariton (LRSPP) in gold strip waveguides. The plasmonic waveguides are fabricated in-house, and contain a gold layer, tantalum pentoxide adhesion layers, and silicon dioxide cladding. The optical characterization was performed using a high power picosecond laser at 1064 nm. The experiments reveal two nonlinear optical effects: nonlinear power transmission and spectral broadening of the LRSPP mode in the waveguides. Both nonlinear optical effects depend on the gold layer thickness. The theoretical model of these effects is based on the third-order susceptibility of the constituent materials. The linear and nonlinear parameters of the LRSPP mode are obtained, and the nonlinear Schrödinger equation is solved. The dispersion length is much larger than the waveguides length, and the chromatic dispersion does not affect the propagation of the plasmonic mode. We find that the third-order susceptibility of the gold layer has a dominant contribution to the effective third-order susceptibility of the LRSPP mode. The real part of the effective third-order susceptibility leads to the observed spectral broadening through the self-phase modulation effect, and its imaginary part determines the nonlinear absorption parameter and leads to the observed nonlinear power transmission. The experimental values of the third-order susceptibility of the gold layers are obtained. They indicate an effective enhancement of the third order susceptibility for the gold layers, comparing to the bulk gold values. This enhancement is explained in terms of the change of the electrons motion.

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Optical bound state in the continuum in the one-dimensional photonic crystal slab: Theory and experiment
In this work, we implement CMOS-compatible one-dimensional photonic structure based on silicon-on-insulator wafer supporting optical bound states in the continuum at telecommunication wavelengths — localized optical state with energy
lying above the light line of the surrounding space. Such high-Q states are very promising for many potential applications ranging from on-chip photonics and optical communications to biological sensing and photovoltaics.

**General information**

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**Surface waves on metal-dielectric metamaterials**

In this paper we analyze surface electromagnetic waves supported at an interface between an isotropic medium and an effective anisotropic material that can be realized by alternating conductive and dielectric layers with deep subwavelength thicknesses. This configuration can host various types of surface waves and, therefore, can serve as a platform allowing many applications for surface photonics. Most of these surface waves are directional and their propagation direction is sensitive to permittivities of the media forming the interface. Hence, their propagation can be effectively controlled by changing a wavelength or material parameters. We discover that two new types of surface waves with complex dispersion exist for a uniaxial medium with both negative ordinary and extraordinary permittivities. Such new surface wave solutions originate from the anisotropic permittivities of the uniaxial media, resulting in unique hyperbolic–like wavevector dependencies.

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**Surface Waves on Metamaterials Interfaces**

We analyze surface electromagnetic waves supported at the interface between isotropic medium and effective anisotropic material that can be realized by alternating conductive and dielectric layers. This configuration can host various types of surface waves and therefore can serve as a rich platform for applications of surface photonics. Most of these surface waves are directional and as such their propagation can be effectively controlled by changing wavelength or material parameters tuning.
Adiabatic Nanofocusing of Short-Range SPPs

Boosting Local Field Enhancement by on-Chip Nanofocusing and Impedance-Matched Plasmonic Antennas

Strongly confined surface plasmon-polariton modes can be used for efficiently delivering the electromagnetic energy to nanosized volumes by reducing the cross sections of propagating modes far beyond the diffraction limit, that is, by nanofocusing. This process results in significant local-field enhancement that can advantageously be exploited in modern optical nanotechnologies, including signal processing, biochemical sensing, imaging, and spectroscopy. Here, we propose, analyze, and experimentally demonstrate on-chip nanofocusing followed by impedance-matched nanowire antenna excitation in the end-fire geometry at telecom wavelengths. Numerical and experimental evidence of the efficient excitation of dipole and quadrupole (dark) antenna modes are provided, revealing underlying physical mechanisms and analogies with the operation of plane-wave Fabry-Pérot interferometers. The unique combination of efficient nanofocusing and nanoantenna resonant excitation realized in our experiments offers a major boost to the field intensity enhancement up to ~12000, with the enhanced field being evenly distributed over the gap volume of 30 × 30 × 10 nm³, and promises thereby a variety of useful on-chip functionalities within sensing, nonlinear spectroscopy and signal processing.
Deep subwavelength photonic multilayers fabricated by atomic layer deposition

General information
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Experimental Demonstration of Effective Medium Approximation Breakdown in Deeply Subwavelength All-Dielectric Multilayers

We report the first experimental demonstration of anomalous breakdown of the effective medium approximation in all-dielectric deeply subwavelength thickness (d∼λ/160–λ/30) multilayers, as recently predicted theoretically [H. H. Sheinfux et al., Phys. Rev. Lett. 113, 243901 (2014)]. Multilayer stacks are composed of alternating alumina and titania layers fabricated using atomic layer deposition. For light incident on such multilayers at angles near the total internal reflection, we observe pronounced differences in the reflectance spectra for structures with 10- vs 20-nm thick layers, as well as for structures with different layers ordering, contrary to the predictions of the effective medium approximation. The reflectance difference can reach values up to 0.5, owing to the chosen geometrical configuration with an additional resonator layer employed for the enhancement of the effect. Our results are important for the development of new high-precision multilayer ellipsometry methods and schemes, as well as in a broad range of sensing applications.

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Improved Coupling to Plasmonic Slot Waveguide via a Resonant Nanoantenna

Plasmonic waveguides are considered as a future generation of optical interconnects in integrated circuits for datacom technologies due to their extreme field confinement performance. Inevitably, when using nanoscale waveguides, a new challenge emerges: how to effectively couple the diffraction-limited optical waves into deep-subwavelength plasmonic waveguides. In this contribution we provide a systematic approach to design, fabricate and characterize an efficient, broadband, and compact dipole antenna nanocoupler for the telecom wavelength range around 1.55 µm. We consider the vertical coupling configuration with a realistic excitation directly from an optical fiber. The scattering-type scanning near-field optical microscope (s-SNOM) characterization allows us not only to make relative comparison of the efficiencies (in terms of the effective area) of different couplers, but also to measure the effective index and propagation length of the slot waveguide mode. All experimental data are in very good correspondence with the numerical simulations. It was also confirmed that the serially connected dipole antennas represent the most efficient and simple design of nanocouplers. We report 26- and 15-fold improvements in the coupling efficiency with two serially connected dipole and modified bow-tie antennas, respectively, as compared to that of the short-circuited waveguide termination. We also emphasize that the s-SNOM-based characterization procedure will become a standard robust technique for the plasmonic waveguide characterization due to its high resolution and reliable measurements.
Metamaterial-based Design for a Half Wavelength Plate in the Terahertz Range

In this work a new design aimed to perform as a half-wavelength plate in the terahertz regime is presented. The fabricated samples exhibit a phase difference of 180 degrees at 0.73 THz between the two principal polarizations that matches with the modelling results. The experimentally determined transmittances of the two polarisations were around 61%, which is below theoretical predictions of reaching more than 90%. The difference between the two results is explained and possibilities for increasing the transmittance are presented.
Metasurfaces for Terahertz Waves Polarization Control

Metamaterials as the design concept and umbrella name have demonstrated a broad range of useful properties in different ranges of frequencies. The main advantage of the metamaterial-based devices is the possibility to broaden both passive and active photonic component functionalities. While in the visible, near infrared or microwave regimes these issues in principle have strong alternatives via a conventional optics or electromagnetic approaches, at terahertz (THz) frequencies metamaterials are often considered as being the unique solution for the encountered problems. Several approaches involving metamaterials-based THz components have been proposed and show good potential for applications [1, 2]. Especially fruitful appears to be two-dimensional metamaterials or metasurfaces due to fabrication simplifications and practically the same as bulk metamaterials functionalities. In the talk we will focus on employment of THz metasurfaces as polarizers and polarization converters, absorbers and conducting layers with enhanced transmittance, dichroic and chiral reconfigurable systems, waveplates and broadband filters. As the unified approach we employ the transmission line theory providing a needed level of the generalization. We demonstrate its applicability in optical problems by analyzing the theoretical limits of a metasurface converter with orthogonal linear eigenpolarizations that allows for linear-to-elliptical polarization transformation with any desired ellipticity and ellipse orientation. Our analysis reveals that the maximal conversion efficiency with a single metamaterial surface is 50 % in transmission and up to 90% in reflection. However, a double layer transmission converter and a single layer with a metallic mirror can have 100% polarization conversion efficiency. We tested our conclusions numerically reaching the designated limits of efficiency using a simple metamaterial design and checking them against the numbers reported in literature. The metasurfaces performance was characterized by exemplifying them with free-standing membranes patterned with a grid of air slits perforated in a uniform large area (up to several cm2) 2μm-thick Ni film. Depending on arrangement of both slits and their sizes different optical properties of such metasurface can be acquired. We demonstrate linear polarization filtering with the parallel slits dimmers, and more complex chiral behaviour of dimers, when non-equal slits are non-parallel. In particular, strong optical activity and circular polarization conversion are reported.
Optical Nano-antennae as Compact and Efficient Couplers from Free-space to Waveguide Modes

Optical nano-antennae are one of the possible solutions for coupling free-space radiation into subwavelength waveguides. Our efforts were concentrated on coupling between an optical fibre and a plasmonic slot waveguide. Such coupling is still an issue to be solved in order to advance the use of plasmonic waveguides for optical interconnects. During the talk, we will present our modelling optimisation, fabrication and measurement of the nano-antennae functionality. For the modelling part, we used CST Microwave studio for optimising the antenna geometry. Various antennae were modelled and fabricated. The fabrication was based on electron beam lithography and lift-off processes. The measurements were performed with scattering scanning near-field microscope and allowed the retrieval of both amplitude and phase of the propagating plasmon. The obtained values agree very well with the theoretically predicted ones thus validating our approach.

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Polarization-Independent Wideband High-Index-Contrast Grating Mirror

Island-type two-dimensional high-index-contrast grating mirror based on a standard silicon-on-insulator wafer have been experimentally demonstrated. The measured spectra shows a bandwidth of ~192 nm with a reflectivity over 99% as well as polarization independence. Numerical simulations show that the designed mirror has large tolerance to fabrication errors.

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Selective Electroless Silver Deposition on Graphene Edges

We demonstrate a method of electroless selective silver deposition on graphene edges or between graphene islands without covering the surface of graphene. Modifications of the deposition recipe allow for decoration of graphene edges with silver nanoparticles or filling holes in damaged graphene on silica substrate and thus potentially restoring electric connectivity with minimal influence on the overall graphene electrical and optical properties. The presented technique could find applications in graphene based transparent conductors as well as selective edge functionalization and can be extended to other metals than silver.
TiO₂ and Al₂O₃ ALD Grown Multilayers for Subwavelength Photonics

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Ultra-thin films for plasmonics: a technology overview

Ultra-thin films with low surface roughness that support surface plasmon-polaritons in the infra-red and visible ranges are needed in order to improve the performance of devices based on the manipulation of plasmon propagation. Increasing amount of efforts is made in order not only to improve the quality of the deposited layers but also to diminish their thickness and to find new materials that could be used in this field. In this review, we consider various thin films used in the field of plasmonics and metamaterials in the visible and IR range. We focus our presentation on technological issues of their deposition and reported characterization of film plasmonic performance.

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Ultra-thin Metal and Dielectric Layers for Nanophotonic Applications
In our talk we first give an overview of the various thin films used in the field of nanophotonics. Then we describe our own activity in fabrication and characterization of ultra-thin films of high quality. We particularly focus on uniform gold layers having thicknesses down to 6 nm fabricated by e-beam deposition on dielectric substrates and Al-oxides/Ti-oxides multilayers prepared by atomic layer deposition in high aspect ratio trenches. In the latter case we show more than 1:20 aspect ratio structures can be achieved.

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With advances in the plasmonics and metamaterials research field, it has become more and more important to fabricate thin and smooth Au metal films in a reliable way. Here, by thin films we mean that their average height is below 10 μm and their average roughness is below 5% of the total thickness. In this article, we investigated the use of amino- and mercaptosilanes to increase the adhesion of Au on Si wafers, thus obtaining a smooth and thin layer. This method does not include the use of other metals to improve the adhesion of gold, like Ti or Cr, since they would reduce the optical characteristics of the structure. Our results show that layers having 6 nm thickness and below 0.3 nm roughness can be reproducibly obtained using aminosilanes. Layers having a nominal thickness of 5 nm have a yield of 58%; thus, this thickness is the limit for the process that we investigated.
Direct Characterization of Plasmonic Slot Waveguides and Nanocouplers

We demonstrate the use of amplitude- and phase-resolved near-field mapping for direct characterization of plasmonic slot waveguide mode propagation and excitation with nanocouplers in the telecom wavelength range. We measure mode’s propagation length, effective index and field distribution and directly evaluate the relative coupling efficiencies for various couplers configurations. We report 26- and 15-fold improvements in the coupling efficiency with two serially connected dipole and modified bow-tie antennas, respectively, as compared to that of the short-circuited waveguide termination.

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Linear and nonlinear properties of chalcogenide glasses in the terahertz frequency

Terahertz (THz) waves have the potential to improve a wide range of devices in the space, defense and semiconductor industries as well as offering the possibility of investigating various molecules of interest in biology, medicine, art etc. For this reason, THz sources, detectors and passive linear components have greatly been developed in recent years. However there is still no any non-linear device available. This is mainly due to the lack of the rigorous investigation of non-linear characteristics of materials in the THz range. We chose to investigate chalcogenide glasses due to their high nonlinear coefficients in the optical range, which might suggest pronounced nonlinear behavior also at THz frequencies. Here we present measurements, both linear and nonlinear, of As2S3 and As2Se3. For the linear measurements we employed a combination of THz time-domain spectroscopy setups. In the low frequency range we used a standard THz-TDS setup based on photoconductive switches while in the higher frequency domain we used an air biased coherent detection (ABCD) setup. This allowed for a wide frequency range (from 0.2 to 18 THz) investigation of the refractive index of the glasses. The nonlinear coefficient in the THz range was investigated using a lithium niobate based setup that allows us to reach electrical field strength exceeding 400 kV/cm. Results from both investigations will be presented during the talk.
Metal membrane with dimer slots as a universal polarizer

In this work, we show theoretically and confirm experimentally that thin metal membranes patterned with an array of slot dimers (or their Babinet analogue with metal rods) can function as a versatile spectral and polarization filter. We present a detailed covariant multipole theory for the electromagnetic response of an arbitrary dimer based on the Green functions approach. The theory confirms that a great variety of polarization properties, such as birefringence, chirality and elliptical dichroism, can be achieved in a metal layer with such slot-dimer patterning (i.e. in a metasurface). Optical properties of the metasurface can be extensively tuned by varying the geometry (shape and dimensions) of the dimer, for example, by adjusting the sizes and mutual placement of the slots (e.g. inter-slot distance and alignment angle). Three basic shapes of dimers are analyzed: H-shaped (parallel slots), V-shaped, and T-shaped. These particular shapes of dimers are found to be sensitive to variations of the slots lengths and orientation of elements. Theoretical results are well supported by full-wave three-dimensional simulations. Our findings were verified experimentally on the metal membranes fabricated using UV lithography with subsequent Ni growth. Such metasurfaces were characterized using time-domain THz spectroscopy. The samples exhibit pronounced optical activity (500 degrees per wavelength) and high transmission: even though the slots cover only 4.3 % of the total membrane area the amplitude transmission reaches 0.67 at the resonance frequency 0.56 THz.

Metal nanoparticles for thin film solar cells

Among the different renewable ways to produce energy, photovoltaic cells have a big potential and the research is now focusing on getting higher efficiency and at the same time saving the manufacturing costs improving the performance of thin film solar cells.

The spectral distribution in the infrared wavelength region longer than 800 nm accounts for ~40% of the entire solar energy observed on Earth, and only a few solar cells can efficiently convert solar energy with such a long wavelength. The goal of this work is the harvesting of these NIR photons in order to increase the solar cells efficiency in such spectral range; after an overview of the different technologies available today, the employment of localized surface plasmons (LSPs) through the incorporation of metallic nanoparticles within the photovoltaic device is chosen as a cheap and simple method.

The LSP resonance wavelength and intensity depends on the nanoparticle’s size, shape, and local dielectric environment,
thus absorption enhancement in a defined wavelength range can be achieved varying these properties (tuning the LSP resonance). Even though scattering enhancement of photons above the gap of the semiconductor is useful to increase light trapping and can come along regardless, we aim, as first target, to absorb forbidden (for the semiconductor) photons by the NPs which can excite hot electrons inside the metal NP and emit them directly into the conduction band of the solar cell semiconductor, without going through the promotion of electrons from the valence band of the semiconductor. The photoemission would extend the spectral response of the photovoltaic device.

Thus, NPs are placed at the metal/semiconductor interface (in order to exploit the localization characteristic of the LSP enhancement) and are used as active nanoantennas absorbing photons with energy smaller than the semiconductor gap but larger than the Schottky barrier height between metal and semiconductor.

The optimization of the fabrication process of GaAs and a-Si:H Schottky solar cells is first conducted and subsequently, the incorporation of Au or Ag nanoparticles at the interface between the semiconductor and a transparent conductive oxide layer (TCO), used to complete the Schottky junction and as top electrode, has followed.

A model representing the device structure with GaAs, ITO and incorporated Au disks or Ag ellipsoids in between, is developed and used for FDTD simulations, in order to identify the set of parameters (NPs size and array periodicity) which could show LSP resonance in the NIR range.

Two techniques are here used to fabricate NPs: electron beam lithography (EBL), to deposit ordered arrays of gold and silver NPs, simple to be compared with modelling; and electrolest plating, to grow silver nanocrystals with a cheap technology, producing random distribution of particles. These techniques are studied and optimized aiming to obtain NPs patterns of different size, periodicity and density on the substrates required for the incorporation within the solar cell structure (GaAs, SiO\textsubscript{2}, Si\textsubscript{3}N\textsubscript{4}, AZO/Cr), in order to investigate the LSP resonance and tune it to exploit it below the energy band gap of the semiconductor.

EBL is a difficult technique when working on critical size (20-50 nm) nanoparticles. The optimization of the process saw a change from ZEP resist to double layer of PMMA and always requires preliminary exposure dose-tests and final particular attention for lift-off step. EBL resulted to be more suitable for silver NPs, since the deposition of gold (on top of an adhesion thin titanium layer) leads to a variation and non-regularity in the shape of the NPs: truncated cones with varying bottom and top radius. The difference in shape causes broadening of the resonance peak (as demonstrated by simulations).

Electroless plating is a technique, based on chemical reactions, which makes use, in the process chosen for this work, of Ag\textsubscript{NO\textsubscript{3}} powder, diluted in water, and HF at very low concentrations. This kind of deposition is very cheap but precise optimization of recipes, strictly depending on the substrate surface, is needed and limited by the chemistry involved. Thus, the NPs grown with this method are characterized by broad distribution of size and shape of NPs bigger than what can be obtained by EBL.

The nanoparticles, after being deposited on different substrates and eventually coated with TCO, are first optically characterized: reflection and transmission are measured with an integrating sphere and consequent absorption spectra are calculated.

A variety of metal nanoparticles on GaAs and a-Si:H is studied. Only Ag nanoparticles have measurable photon absorption while no effect is seen with Ti/Au nanoparticles. SEM and AFM measurements show that size, shape and height are very variable with Ti/Au nanoparticles fabricated by EBL, within the pattern, and this combined with small density of patterns might be a reason for the unmeasurable absorbance enhancement.

The behavior of ordered Ag NPs fabricated by EBL depends on their size and thickness: 24-34 nm of diameter, array pitch of 100 nm and 15-30 nm of thickness give absorbance enhancement in the visible range between 500 and 600 nm of wavelength. Ag NPs of 20-34 nm size and 30 nm thick, incorporated into a-Si:H solar cell structure (thus covered by TCO) with varying array pitch (60/80/100 nm) show 3 localized surface plasmon resonances (LSPR): around 450 nm, 560 nm and 740 nm. LSPR at 560nm originates from scattering, while LSPRs at 450nm and 740nm, are due to NPs absorption. The tail of the peak at 740nm, falls below the gap of the semiconductor (a-Si:H) and the energy of the photons exciting the LSPs, can be translated in consequent emission of hot electrons.

Random Ag NPs patterns fabricated by electrolest plating are characterized by larger size (from 60 nm) and, if characterized by filling fraction higher than 15%, they give significant absorbance enhancement (20%) in the NIR range regardless the size or shape and already without TCO coating. This enhancement is caused by a huge suppression in transmission and can be exploited to promote photoemission in PV devices.

EELS measurements are conducted on Ag NPs deposited by electrolest plating in order to investigate the nature of the absorption enhancement, which is not found on similar ordered patterns. Particular dimers (forming nano-bridges) and elongated particles are the responsible of the plasmonic excitations in the energy range of 0.9-1.5 eV, corresponding to part of the NIR range characterized by absorbance enhancement.

Finally, after optical characterization, the NPs are incorporated within the entire diode structure and electrically characterized.

Spectral responses are measured and in two types of measured GaAs solar cells (with Au and Ag nanoparticles) there was no clear efficiency enhancement in the NIR spectral range. In the case of Au nanoparticles it could be explained in similar way to the absorption data: the effect being broad is too weak. The absence of the expected plasmonic enhancement below the gap in devices with Ag NPs suggests that the energy of absorbed photons does not lead to photoemission but is dissipated through heat. GaAs is known to have very fast surface recombination and possibly it was not reduced well enough with the introduced Si\textsubscript{3}N\textsubscript{4} layer.

On the other hand, quantum efficiency of a-Si:H solar cells show enhancement corresponding to the 3 LSPRs found in absorption spectra, but absorption contribute by NPs is enhanced by LSP less effectively than scattering; furthermore, it is also less effective than absorption in semiconductor so really only worth it if the peak can be shifted below the bandgap. Finally, the variability of the enhancement corresponding to the resonances due to absorption is hard to understand, thus possible surface recombination, due to processing variations, might play an important role.
Further developments are needed in the solar cell structure in order to reduce surface recombination and exploit the photoemission below the semiconductor energy gap; nevertheless, promising optical results showed here confirmed the possibility to use nanostructures, in particular randomly distributed, to extend solar cells spectral response to longer wavelengths, through possibly cheap and simple technologies: EBL can be substituted by colloidal solutions implementation and electroless plating is not expensive and results to be effective within a broad set of parameters (size, shape, density). Another application of the studied NPs can be in NIR photodetectors.

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Nanoplasmonic solution for nonlinear optics
Nonlinear optical properties of dielectric waveguides are well known and are widely used in modern telecommunication systems [1]. However, the fundamental law of diffraction imposes physical limitation for integration of dielectric photonics and semiconductor electronics [2]. A possible way to combine the high speed of a photonic device with the compact size of an electronic device is to produce an nanoplasmonic device based on metal waveguides. The successful solutions can be used for future sustainable technologies. In meantime, nonlinear optics of metal waveguides is not fully understood and is being under investigation in recent years [3]. The purpose of our research is to study nonlinear optical properties of gold waveguides embedded into dielectric medium (silicon dioxide) using picosecond laser spectroscopy. The work includes modeling of optical properties of gold waveguides, fabrication of prototype samples, and optical characterization of samples using a picosecond laser source. The prototype samples of gold waveguides embedded into silicon dioxide were fabricated at DTU Danchip. A silicon wafer with pre-made 6.5 μm layer of silicon dioxide was used as a substrate and gold waveguides (films) with the thickness of 35 nm were deposited using the sputter system (Lesker). The waveguides have different widths in the range of 1 μm to 100 μm. A cladding layer of silicon dioxide of about 5 μm was deposited on top of the gold waveguides using the plasma-enhanced chemical vapor deposition (PECVD) method. The quality of samples was inspected using the optical microscope, scanning electron microscope, atomic force microscope, and ellipsometer. The ready wafer was diced into several rectangular slices with the fixed width of 15 mm and the different length from 2 mm to 6 mm for optical characterization in the laboratory. The samples were characterized using the picosecond laser source (NKT Photonics) with the peak wavelength of 1064 nm. The relevant spectra are shown on picture 1. The red curve corresponds to the reference measurement of the laser spectrum. The green curve is the transmission spectrum for the silicon dioxide cladding. The blue, cyan and magenta curves correspond to the transmission spectra for the gold waveguides with the width of 10 μm and length of 2, 3, and 4 mm. The polarization of laser beam was tuned to match the transverse magnetic mode of surface plasmon polaritons in the gold waveguides. The propagation loss per unit length and coupling loss for the gold wave guides were calculated. The average propagation loss was 14 dB/mm and the average coupling loss was 6 dB. The obtained results showed a capability of the prototype samples to guide surface plasmon polaritons and their potential for the further investigation of nonlinear properties.

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Plasmonic Antennas Nanocoupler for Telecom Range: Simulation, Fabrication and Near-Field Characterization
We report simulation, fabrication and, for the first time, full amplitude-phase near-field optical characterization in telecom range of the compact and efficient plasmonic nanoantenna based couplers. Near-field data allowed characterizing the subwavelength slot waveguide’s propagation losses and effective mode index that correspond well to the simulated ones.
Resonant field enhancement in periodically arranged microslits for non-linear terahertz spectroscopy

We present a design of periodically arranged microslits in a gold film for nonlinear terahertz phonon spectroscopy. Global optimization of array parameters gives a field enhancement of more than 50, due to plasmonic coupling between individual slits.

Simulation, Fabrication and Near-Field Characterization of Nanoantenna Couplers for Telecom Range

We report a modified bow-tie antenna for light coupling to subwavelength plasmonic slot waveguide. Its effective area is 15 times larger than that of the bare waveguide termination at the wavelength 1.55 µm. We demonstrate numerical simulation, fabrication and, for the first time, full amplitude-phase near-field optical characterization of nanocoupler in telecom range.
**Super-resolution near field imaging device**

Super-resolution imaging device comprising at least a first and a second elongated coupling element, each having a first transverse dimension at a first end and a second transverse dimension at a second end and being adapted for guiding light between their respective first and second ends, each further comprising a dielectric center element and a metallic side-wall region, which surrounds the dielectric center element. The coupling elements are arranged in a matrix comprising a matrix material and the first ends of the coupling elements are located at or in a vicinity of the first side of the matrix and the second ends of the coupling elements are located at or in a vicinity of the second side of the matrix. The second transverse dimension is larger than the first transverse dimension. A microscope objective system and a microscope comprising the super-resolution imaging device are also claimed.

**Fabrication and characterization of transparent metallic electrodes in the terahertz domain**

The demand for transparent electrodes keeps increasing as new generations of electronic devices appear, including solar cells and touch screens. Indium tin oxide (ITO) is the most promising transparent electrode material to date [1] although there are several limitations when using ITO. Firstly, it is a brittle material and therefore flexible devices such as electronic paper would be hard to achieve. Secondly, the continuous increase in the price of indium due to limited availability worldwide makes its use unsustainable in the future.

Our work is motivated by early work [2] showing that an optically opaque layer with a negative permittivity can be perfectly transparent when sandwiched between two carefully designed metamaterial layers. Here we present a method to achieve a transparent metallic electrode deposited on a substrate. By placing a composite layer consisting of dielectric and metallic stripes (AB layer) on top of the metallic electrode (C layer) (see Fig. 1(a)) we found that the backscattering from the metallic film (C layer) can be almost perfectly canceled, leading to transparency of the whole structure. We fabricated the transparent metallic electrodes and characterized them by the use of the T-Ray 4000 terahertz time-domain spectroscopy system. The physics behind the cancellation of the scattering from the target opaque layer requires carefully chosen geometrical parameters of the metamaterial layers, AB and C, (see Fig. 1(b)). Figure 1(c) displays the transmittance through the whole sample normalized to that through the silicon substrate. The transmittance through the C layer mesh is quite low for the frequency range 0.2 - 0.8 THz, reaching its maximum of approximately 0.45 at 0.8 THz. By placing the AB mesh on top of the C layer separated by 12.5 μm silica, the ABC device achieves almost a perfect transmittance at 0.57 THz. Moreover, in the frequency range 0.3 - 0.6 THz the ABC device has still higher transmittance than the C layer alone. Our experimental results match nicely with the full-wave simulations (solid lines, Fig. 1(c)) [3].
Fabrication approaches for plasmon-improved photovoltaic cells
During this talk we will present various fabrication approaches to improve the performance of photovoltaic (PV) cells by using metallic nanoparticles in order to generate photocurrent below the bandgap. This effect is possible due to the generation of surface plasmon polaritons (SPPs) in optimized nanoparticles.

General information
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Organisations: Department of Photonics Engineering, Plasmonics and Metamaterials, Forschungs Zentrum Jülich GmbH
Authors: Gritti, C. (Intern), Malureanu, R. (Intern), Kardynal, B. (Ekstern), Lavrinenko, A. (Intern)
Number of pages: 2
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Main Research Area: Technical/natural sciences
Electronic versions:
prod11373890775958.Fabrication_approaches_for_plasmon_improved_photovoltaic_cells.pdf

Bibliographical note
Invited talk in session: Plasmonic nanocomposites: fabrication to function (2A18).
Publication: Research - peer-review › Paper – Annual report year: 2013

Metamaterial polarization converter analysis: limits of performance
In this paper, we analyze the theoretical limits of a metamaterial-based converter with orthogonal linear eigenpolarizations that allow linear-to-elliptical polarization transformation with any desired ellipticity and ellipse orientation. We employ the transmission line approach providing a needed level of the design generalization. Our analysis reveals that the maximal conversion efficiency for transmission through a single metamaterial layer is 50 %, while the realistic reflection configuration can give the conversion efficiency up to 90 %. We show that a double layer transmission converter and a single layer with a ground plane can have 100 % polarization conversion efficiency. We tested our conclusions numerically reaching the designated limits of efficiency using a simple metamaterial design. Our general analysis provides useful guidelines for the metamaterial polarization converter design for virtually any frequency range of the electromagnetic waves.

General information
State: Published
Organisations: Department of Photonics Engineering, Plasmonics and Metamaterials, National Research University of Information Technologies
Authors: Markovich, D. L. (Ekstern), Andryieuski, A. (Intern), Zalkovskij, M. (Intern), Malureanu, R. (Intern), Lavrinenko, A. V. (Intern)
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BFI (2015): BFI-level 1
Scopus rating (2015): SJR 0.931 SNIP 1.112 CiteScore 1.74
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 1
Scopus rating (2014): SJR 1.089 SNIP 1.256 CiteScore 1.96
BFI (2013): BFI-level 1
Scopus rating (2013): SJR 1.04 SNIP 1.181 CiteScore 1.92
ISI indexed (2013): ISI indexed yes
Metamaterials and Metasurfaces in THz Applications
We present a set of terahertz optical components, such as linear and circular polarizers, absorbers, devices with enhanced transmittance, and single layer chiral systems based on metamaterials. Discussion covers design rules, fabrication and characterization.

General information
State: Published
Organisations: Department of Photonics Engineering, Plasmonics and Metamaterials, Terahertz Technologies and Biophotonics, Bergische Universität Wuppertal, Fudan University
Number of pages: 2
Publication date: 2013
Optically active Babinet planar metamaterial film for terahertz polarization manipulation

A planar Babinet-inverted dimer metamaterial possessing strong optical activity is proposed and characterized. An original fabrication method to produce large area (up to several cm²) freely suspended flexible metallic membranes is implemented to fabricate the metamaterial. Its optical properties are characterized by terahertz time-domain spectroscopy, revealing anisotropic transmission with high optical activity. A simple coupled resonator model is applied to explain the principal optical features of the dimers, with predictive power of positions and number of resonances through a parametrical model. The model is validated for correct polarization-dependent quantitative results on the optical activity in transmission spectra. The fabrication method presented in this work as well as the slit dimer design has great potential for exploitation in terahertz optics.
Optimization design of optical waveguide control by nanoslit-enhanced THz field

We discuss design issues of devices which were proposed recently [Opt. Lett. 37 (2012) 3903] for terahertz (THz) control of the propagation of an optical waveguide mode. The mode propagates through a nonlinear dielectric material placed in a metallic nanoslit illuminated by THz radiation. The THz field in the slit is strongly localized and thus significantly enhanced, facilitating nonlinear interactions with the dielectric waveguide material. This enhancement can lead to notable changes in the refractive index of the waveguide. The closer the waveguide is to the slit walls, the higher the nonlinear effects are, but with the cost of increasing propagation losses due to parasitic coupling to surface plasmon polaritons at the metal interfaces. We analyze several optical waveguide configurations and define a figure of merit that allows us to design the optimal configuration. We find that designs with less overlap of the THz and optical fields but also with lower losses are better than designs where both these parameters are higher. The estimated terahertz field incident onto the metallic nanoslit required to manipulate the waveguide mode has reasonable values which can be achieved in practice.

General information
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Organisations: Department of Photonics Engineering, Plasmonics and Metamaterials, Terahertz Technologies and Biophotonics
Authors: Novitsky, A. (Intern), Malureanu, R. (Intern), Zalkovskij, M. (Intern), Jepsen, P. U. (Intern), Lavrinenko, A. (Intern)
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Publication date: 2013
Main Research Area: Technical/natural sciences

Publication information
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BFI (2017): BFI-level 1
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BFI (2016): BFI-level 1
Scopus rating (2016): SJR 0.621 SNIP 0.882 CiteScore 1.8
BFI (2015): BFI-level 1
Scopus rating (2015): SJR 0.749 SNIP 0.715 CiteScore 1.56
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BFI (2014): BFI-level 1
Scopus rating (2014): SJR 0.746 SNIP 0.801 CiteScore 1.54
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 1
Scopus rating (2013): SJR 0.842 SNIP 0.785 CiteScore 1.67
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BFI (2012): BFI-level 1
Scopus rating (2012): SJR 0.972 SNIP 1.159 CiteScore 1.73
ISI indexed (2012): ISI indexed yes
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BFI (2011): BFI-level 1
Scopus rating (2011): SJR 1.333 SNIP 1.172 CiteScore 2.29
ISI indexed (2011): ISI indexed yes
Plasmonic Dimer Metamaterials and Metasurfaces for Polarization Control of Terahertz and Optical Waves

We explore the capabilities of planar metamaterials and metasurfaces to control and transform the polarization of electromagnetic radiation, and present a detailed covariant multipole theory of dimer-based metamaterials. We show that various optical properties, such as optical activity, elliptical dichroism or polarization conversion can be achieved in metamaterials made of simple shapes, such as nanorods, just by varying their geometrical arrangement. By virtue of the Babinet principle, the proposed theory is extended to inverted structures (membranes) where rods are replaced by slots. Such free-standing “metasurface membranes” can act as thin-film spectrally sensitive polarization shapers for THz radiation. Proof-of-principle devices (a linear polarizer and a structure with giant optical activity) are fabricated and characterized. Experimental results coincide with those of full-wave numerical simulations, and are in good agreement with analytical predictions.

General information

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Organisations: Department of Photonics Engineering, Plasmonics and Metamaterials, Terahertz Technologies and Biophotonics, Institute for Product Development, University of Wuppertal
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Main Research Area: Technical/natural sciences
Conference: 15th International Conference on Transparent Optical Networks (ICTON), Cartagena, Spain, 23/06/2013 - 23/06/2013
DOIs: 10.1109/ICTON.2013.6603017
Source: dtu
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Publication: Research - peer-review › Article in proceedings – Annual report year: 2013

Plasmonic finite-thickness metal-semiconductor-metal waveguide as ultra-compact modulator

We propose a plasmonic waveguide with semiconductor gain material for optoelectronic integrated circuits. We analyze properties of a finite-thickness metal-semiconductor-metal (F-MSM) waveguide to be utilized as an ultra-compact and fast plasmonic modulator. The InP-based semiconductor core allows electrical control of signal propagation. By pumping the core we can vary the gain level and thus the transmittance of the whole system. The study of the device was made using
both analytical approaches for planar two-dimensional case as well as numerical simulations for finite-width waveguides. We analyze the eigenmodes of the F-MSM waveguide, propagation constant, confinement factor, Purcell factor, absorption coefficient, and extinction ratio of the structure. We show that using thin metal layers instead of thick ones we can obtain higher extinction ratio of the device.

**General information**

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Organisations: Department of Photonics Engineering, Plasmonics and Metamaterials
Authors: Babicheva, V. (Intern), Malureanu, R. (Intern), Lavrinenko, A. (Intern)
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ISI indexed (2013): ISI indexed yes
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Scopus rating (2012): SJR 0.972 SNIP 1.159 CiteScore 1.73
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Scopus rating (2011): SJR 1.333 SNIP 1.172 CiteScore 2.29
ISI indexed (2011): ISI indexed yes
BFI (2010): BFI-level 1
Scopus rating (2010): SJR 1.456 SNIP 1.167
Web of Science (2010): Indexed yes
BFI (2009): BFI-level 1
Scopus rating (2009): SJR 1.58 SNIP 0.991
BFI (2008): BFI-level 1
Scopus rating (2008): SJR 1.247 SNIP 1.187
Scopus rating (2007): SJR 1.4 SNIP 1.053
Scopus rating (2006): SJR 1.41 SNIP 0.913
Scopus rating (2005): SJR 1.516 SNIP 1.274
Web of Science (2005): Indexed yes
Scopus rating (2004): SJR 1.391 SNIP 1.302
Web of Science (2003): Indexed yes
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Source: FindIt
Source-ID: 235243825
**Plasmonic modulator based on thin metal-semiconductor-metal waveguide with gain core**

We focus on plasmonic modulators with a gain core to be implemented as active nanodevices in photonic integrated circuits. In particular, we analyze metal–semiconductor–metal (MSM) waveguides with InGaAsP-based active material layers. A MSM waveguide enables high field localization and therefore high modulation speed. The modulation is achieved by changing the gain of the core that results in different transmittance through the waveguide. Dependences on the waveguide core size and gain values of various active materials are studied. The effective propagation constants in the MSM waveguides are calculated numerically. We optimize the structure by considering thin metal layers. A thin single metal layer supports an asymmetric mode with a high propagation constant. Implementing such layers as the waveguide claddings allows to achieve several times higher effective indices than in the case of a waveguide with thick (>50 nm) metal layers. In turn, the high effective index leads to enhanced modulation speed. We show that a MSM waveguide with the electrical current control of the gain incorporates compactness and deep modulation along with a reasonable level of transmittance.

**General information**

State: Published  
Organisations: Department of Photonics Engineering, Plasmonics and Metamaterials  
Authors: Babicheva, V. (Intern), Malureanu, R. (Intern), Lavrinenko, A. (Intern)  
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Journal: Proceedings of SPIE, the International Society for Optical Engineering  
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Web of Science (2016): Indexed yes  
BFI (2015): BFI-level 1  
Scopus rating (2015): SJR 0.187 SNIP 0.224 CiteScore 0.3  
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Scopus rating (2014): SJR 0.188 SNIP 0.231 CiteScore 0.3  
BFI (2013): BFI-level 1  
Scopus rating (2013): SJR 0.2 SNIP 0.259 CiteScore 0.26  
ISI indexed (2013): ISI indexed no  
Web of Science (2013): Indexed yes  
BFI (2012): BFI-level 1  
Scopus rating (2012): SJR 0.194 SNIP 0.243 CiteScore 0.27  
ISI indexed (2012): ISI indexed no  
Web of Science (2012): Indexed yes  
BFI (2011): BFI-level 1  
Scopus rating (2011): SJR 0.197 SNIP 0.264 CiteScore 0.31  
ISI indexed (2011): ISI indexed no  
BFI (2010): BFI-level 1  
Scopus rating (2010): SJR 0.208 SNIP 0.241  
Web of Science (2010): Indexed yes  
BFI (2009): BFI-level 1  
Scopus rating (2009): SJR 0.211 SNIP 0.271  
BFI (2008): BFI-level 1  
Scopus rating (2008): SJR 0.222 SNIP 0.289  
Web of Science (2008): Indexed yes
Plasmonics light modulators

Surface plasmon polaritons (SPPs) are waves propagating at the interface between a metal and a dielectric and, due to their tight confinement, may be used for nanoscale control of the light propagation. Thus, photonic integrated circuits can benefit from devices using SPPs because of their highly compact and fast response time characteristics. In this talk we will present plasmonic modulators with sandwich geometry where the sides are composed of thin metallic layers while the center is an active material with controlled gain coefficient (see figure). In particular, we analyse InGaAsP-based active core. Using such geometry we can obtain high modulation speed, low footprint and high modulation depth. We discuss the dependence of the waveguide core size and gain for different thicknesses of the metallic layers. Due to the finite and small thickness of these layers, several coupled modes can be obtained. We chose only one of these modes to study since calculations showed it is the one allowing for the highest modulation depth while the gain levels needed in order to obtain loss compensation are still within practical reach. Various possibilities for defining the field confinement are discussed as well as relative effective index, absorption coefficient and extinction ratio of the modulator. The differences between the 2D and 3D cases are also succinctly described.

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State: Published
Organisations: Department of Photonics Engineering, Plasmonics and Metamaterials
Authors: Babicheva, V. (Intern), Malureanu, R. (Intern), Lavrinenko, A. (Intern)
Number of pages: 1
Publication date: 2013
Event: Abstract from 15th Photonics North Conference, Ottawa, Canada.
Main Research Area: Technical/natural sciences

Terahertz cross-phase modulation of an optical mode

We discuss an optical scheme which facilitates modulation of an optical waveguide mode by metallic-nanoslit-enhanced THz radiation. The waveguide mode acquires an additional phase shift due to THz nonlinearity with fields reachable in experiments.

General information
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Organisations: Department of Photonics Engineering, Plasmonics and Metamaterials, Terahertz Technologies and Biophotonics
Authors: Lavrinenko, A. (Intern), Novitsky, A. (Intern), Zalkovskij, M. (Intern), Malureanu, R. (Intern), Jepsen, P. U. (Intern)
Pages: CM2J.6
Publication date: 2013
Terahertz-field-induced photoluminescence of nanostructured gold films

We experimentally demonstrate photoluminescence from nanostructured ultrathin gold films subjected to strong single-cycle terahertz transients with peak electric field over 300 kV/cm. We show that UV-Vis-NIR light is being generated and the efficiency of the process is strongly enhanced at the percolation threshold.

General information
State: Published
Organisations: Department of Photonics Engineering, Terahert Technologies and Biophotonics, Plasmonics and Metamaterials
Authors: Iwaszczuk, K. (Intern), Malureanu, R. (Intern), Zalkovskij, M. (Intern), Strikwerda, A. (Intern), Jepsen, P. U. (Intern)
Number of pages: 1
Publication date: 2013

Terahertz-induced Kerr effect in amorphous chalcogenide glasses

We have investigated the terahertz-induced third-order (Kerr) nonlinear optical properties of the amorphous chalcogenide glasses As2S3 and As2Se3. Chalcogenide glasses are known for their high optical Kerr nonlinearities which can be several hundred times greater than those of fused silica. We use high-intensity, single-cycle terahertz pulses with a maximum electrical field strength exceeding 400 kV/cm and frequency content from 0.2 to 3.0 THz. By optical Kerr-gate sampling, we measured the terahertz-induced nonlinear refractive indices at 800nm to be n2 = 1.746 x 10^-14 cm^2/W for As2S3 and n2 = 3.440 x 10^-14 cm^2/W for As2Se3.

General information
State: Published
Organisations: Department of Photonics Engineering, Plasmonics and Metamaterials, Teraherts Technologies and Biophotonics, National Institute for Optoelectronics
Authors: Zalkovskij, M. (Intern), Strikwerda, A. (Intern), Iwaszczuk, K. (Intern), Popescu, A. (Ekstern), Savastru, A. (Ekstern), Malureanu, R. (Intern), Lavrinenko, A. (Intern), Jepsen, P. U. (Intern)
Number of pages: 4
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Scopus rating (2016): CiteScore 2.67 SJR 1.132 SNIP 0.996
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 2
Scopus rating (2015): SJR 1.085 SNIP 0.983 CiteScore 2.47
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 2
Scopus rating (2014): SJR 1.799 SNIP 1.462 CiteScore 3.25
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 2
Scopus rating (2013): SJR 2.149 SNIP 1.652 CiteScore 3.77
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 2
Scopus rating (2012): SJR 2.554 SNIP 1.754 CiteScore 3.76
ISI indexed (2012): ISI indexed yes
Web of Science (2012): Indexed yes
BFI (2011): BFI-level 2
Scopus rating (2011): SJR 2.805 SNIP 1.94 CiteScore 4.04
ISI indexed (2011): ISI indexed yes
Web of Science (2011): Indexed yes
BFI (2010): BFI-level 2
Scopus rating (2010): SJR 2.926 SNIP 1.789
Web of Science (2010): Indexed yes
BFI (2009): BFI-level 2
Scopus rating (2009): SJR 2.857 SNIP 1.848
Web of Science (2009): Indexed yes
BFI (2008): BFI-level 2
Scopus rating (2008): SJR 2.934 SNIP 1.83
Web of Science (2008): Indexed yes
Scopus rating (2007): SJR 3.039 SNIP 1.913
Web of Science (2007): Indexed yes
Scopus rating (2006): SJR 3.457 SNIP 2.288
Web of Science (2006): Indexed yes
Scopus rating (2005): SJR 3.709 SNIP 2.382
Web of Science (2005): Indexed yes
Scopus rating (2004): SJR 3.904 SNIP 2.38
Web of Science (2004): Indexed yes
Scopus rating (2003): SJR 3.765 SNIP 2.27
Web of Science (2003): Indexed yes
Scopus rating (2002): SJR 3.917 SNIP 2.365
Web of Science (2002): Indexed yes
Scopus rating (2001): SJR 4.111 SNIP 2.212
Web of Science (2001): Indexed yes
Scopus rating (2000): SJR 4.277 SNIP 2.013
Web of Science (2000): Indexed yes
Scopus rating (1999): SJR 4.35 SNIP 2.11
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Source: dtu
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Terahertz wave manipulation with metamaterials based on metal and graphene

The terahertz (THz) technology provides with exciting possibilities for spectroscopy, food quality control, defense, communication and biomedical imaging [1]. Being relatively young (the massive exploitation of the THz range began only in the beginning of 1990-ies), the THz science demands for active and passive materials and devices. Metamaterials, metal-dielectric artificial composites, propose wide possibilities for achieving unconventional electromagnetic properties, not found in nature. Moreover, metamaterials constructed of graphene, a monolayer of carbon atoms, allow for tunable response.

In this presentation we overview our results on theory, fabrication and characterization of metal and graphene based metamaterials for the THz range. We show that the multiple layers of structured graphene can form a hyperbolic dispersion medium lens able to resolve the subwavelength features [2]. We analyze the limitations and demonstrate numerically and experimentally the chiral and nonchiral thin-film metamaterial based polarization converters [3–5] and graphene total absorbers for THz radiation [6].

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Organisations: Department of Photonics Engineering, Plasmonics and Metamaterials, Terahertz Technologies and Biophotonics
Pages: 101-102
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Transparent electrodes in the terahertz regime – a new approach

We suggest a new possibility for obtaining a transparent metallic film, thus allowing for completely transparent electrodes. By placing a complementary composite layer on top of the electrode, we can cancel the back-scattering of the latter thus obtaining a perfectly transparent structure. For ease of fabrication, we performed the first experiments in the THz regime, but the concept is applicable to the entire electromagnetic waves spectrum. We show that the experiments and theory match each other perfectly.

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Organisations: Department of Photonics Engineering, Plasmonics and Metamaterials, Terahertz Technologies and Biophotonics, Fudan University
Authors: Malureanu, R. (Intern), Song, Z. (Ekstern), Zalkovskij, M. (Intern), Gritti, C. (Intern), Andryieuski, A. (Intern), He, Q. (Ekstern), Zhou, L. (Ekstern), Jepsen, P. U. (Intern), Lavrinenko, A. (Intern)
Number of pages: 2
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Absorption enhancement in metal nanoparticles for photoemission current for solar cells

In order to improve the photoconversion efficiency, we consider the possibility of increasing the photocurrent in solar cells exploiting the electron photoemission from small metal nanoparticles into a semiconductor. The effect is caused by the absorption of photons and generation of local surface plasmons in the nanoparticles with optimized geometry. An electron photoemission from metal into semiconductor occurs if photon energy is larger than Schottky barrier at the metal-
semiconductor interface. The photocurrent resulting from the absorption of photons with energy below the bandgap of the semiconductor added to the solar cell photocurrent can extend spectral response range of the device. We study the effect on a model system, which is a Schottky barrier n-GaAs solar cell, with an array of Au nanoparticles positioned at the interface between the semiconductor and the transparent top electrode. Based on the simulations, we chose to study disk-shaped Au nanoparticles with sizes ranging from 25nm to 50nm using electron beam lithography. Optical characterization of the fabricated devices shows the presence of LSP resonance around the wavelength of 1250nm, below the bandgap of GaAs.

General information
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Organisations: Department of Photonics Engineering, Plasmonics and Metamaterials, P. N. Lebedev Physical Institute
Authors: Gritti, C. (Intern), Novitsky, A. (Intern), Malureanu, R. (Intern), Lavrinenko, A. (Intern), Uskov, A. (Ekstern), Kardynal, B. (Intern)
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BFI (2015): BFI-level 1
Scopus rating (2015): SJR 0.187 SNIP 0.224 CiteScore 0.3
BFI (2014): BFI-level 1
Scopus rating (2014): SJR 0.188 SNIP 0.231 CiteScore 0.3
BFI (2013): BFI-level 1
Scopus rating (2013): SJR 0.2 SNIP 0.259 CiteScore 0.26
ISI indexed (2013): ISI indexed no
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 1
Scopus rating (2012): SJR 0.194 SNIP 0.243 CiteScore 0.27
ISI indexed (2012): ISI indexed no
Web of Science (2012): Indexed yes
BFI (2011): BFI-level 1
Scopus rating (2011): SJR 0.197 SNIP 0.264 CiteScore 0.31
ISI indexed (2011): ISI indexed no
BFI (2010): BFI-level 1
Scopus rating (2010): SJR 0.208 SNIP 0.241
Web of Science (2010): Indexed yes
BFI (2009): BFI-level 1
Scopus rating (2009): SJR 0.211 SNIP 0.271
BFI (2008): BFI-level 1
Scopus rating (2008): SJR 0.222 SNIP 0.289
Web of Science (2008): Indexed yes
Scopus rating (2007): SJR 0.227 SNIP 0.37
Web of Science (2007): Indexed yes
Scopus rating (2006): SJR 0.308 SNIP 0.701
Scopus rating (2005): SJR 0.158 SNIP 0.343
Web of Science (2004): Indexed yes
A new mechanism to design transparent electrodes: THz realizations
We proposed a simple scheme to make a continuous metallic film on a semi-infinite substrate optically transparent, thus obtaining a completely transparent electrode in a desired frequency range. By placing a sub-wavelength composite layer consisting of dielectric and metallic stripes on top of the metallic one, we found that the back-scattering from the metallic film can be almost perfectly canceled by the composite layer under certain conditions, leading to transparency of the whole structure. Since our mechanism does not require any openings on the opaque metallic plate, the proposed structure retains the full electric and mechanical properties of a natural metal. The present mechanism is insensitive to structural disorders and broad variation of incidence angles. Meanwhile, we performed proof-of-concept experiments in the terahertz domain to verify our theoretical predictions, using carefully designed metamaterials to mimic plasmonic metals in optical regime. Experiments are in excellent agreement with full-wave simulations.

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Organisations: Department of Photonics Engineering, Plasmonics and Metamaterials, Terahertz Technologies and Biophotonics, Fudan University
Authors: Song, Z. (Intern), Malureanu, R. (Intern), Zalkovskij, M. (Intern), Gritti, C. (Intern), Andryieuski, A. (Intern), He, Q. (Intern), Jepsen, P. U. (Intern), Lavrinenko, A. (Intern), Zhou, L. (Forskerdatabase)
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Publication date: 2012

A new method for obtaining transparent electrodes
In this article, we propose a simple scheme to make a metallic film on a semi-infinite substrate optically transparent, thus obtaining a completely transparent electrode in a desired frequency range. By placing a composite layer consisting of dielectric and metallic stripes on top of the metallic one, we found that the back-scattering from the metallic film can be almost perfectly canceled by the composite layer under certain conditions, leading to transparency of the whole structure. We performed proof-of-concept experiments in the terahertz domain to verify our theoretical predictions, using carefully designed metamaterials to mimic plasmonic metals in optical regime. Experiments are in excellent agreement with full-wave simulations.

General information
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Organisations: Department of Photonics Engineering, Plasmonics and Metamaterials, Terahertz Technologies and Biophotonics, Fudan University
Authors: Malureanu, R. (Intern), Zalkovskij, M. (Intern), Song, Z. (Ekstern), Gritti, C. (Intern), Andryieuski, A. (Intern), He, Q. (Ekstern), Zhou, L. (Ekstern), Jepsen, P. U. (Intern), Lavrinenko, A. (Intern)
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Main Research Area: Technical/natural sciences
Anisotropic anti-rod dimer metamaterial film for terahertz polarization manipulation
We demonstrate the concept of an anti-rod dimer planar metamaterial with strong birefringence and optical activity in the THz range. The retrieval of circular transmission components shows an asymmetric transmission effect for right-to-left and left-to-right polarization conversion.

Compact dipole nanoantenna coupler to plasmonic slot waveguide.
Optical nanoantennas can be used for coupling radiation to or from waveguides in analogy to micro- and radio-wave systems. In this letter we provide a systematic description of the design approaches for a coupler to a plasmonic slot waveguide in the telecom range around 1.55 µm with realistic excitation from a lensed optical fiber. We show that the best coupling efficiency of 26% can be achieved by utilizing a dipole antenna with side and bottom reflectors, and such coupling efficiency is 185 times larger than for the bare waveguide. The nanoantenna coupler provides a compact interface between an optical fiber and a plasmonic slot waveguide for future optical integrated circuits.
Fabrication activity for nanophotonics
We present the fabrication and characterization of new structures and materials to be used in nanophotonics. The first structure presented is a fractal metallic metasurface designed to be used as a high-sensitivity sensor for 810nm wavelength. A second structure is a high index contrast grating designed for phase and amplitude control of the transmitted beam. By controlling the Au percentage in a Si matrix, one may be able to obtain high refractive index with very limited loss.

Fabrication and characterization of terahertz anisotropic anti-rod dimer planar metamaterials
In this work we describe the fabrication and characterization of free-standing membranes with thick anti-rod dimers metamaterials for terahertz waves. Two different designs with parallel and V-shape anti-rods were analysed. Even though both structures consists of simple elements, namely anti-rod dimers, they reveal interesting birefringent and dichroic transmission properties.

Finite-thickness metal-semiconductor-metal waveguide as plasmonic modulator
We analyze a finite-thickness metal-semiconductor-metal waveguide to be utilized as an ultra-compact plasmonic modulator in optoelectronic integrated circuits. The InP-based semiconductor core allows electrical control of signal propagation. We show that using thin metal layers instead of thick ones we can obtain higher effective index, which is required for high modulation speed. The ultra-compact layout and tight field confinement are the main advantages of such plasmonic modulators.
Improving plasmonic waveguides coupling efficiency using nanoantennas

Plasmonic waveguides bear a lot of potential for photonic applications. However, one of the challenges for implementing them in devices is the low coupling efficiency to and from optical fibers. We report on our approach to facilitate the coupling efficiency with the use of metallic nanoantennas. The classical dipole antenna scheme can be improved by changing the nanoantenna geometry, adding constructive elements such as reflecting bars and mirrors and using arrays of antennas. The modelling designates that the coupling efficiency from a vertical fiber to a plasmonic waveguide can be improved more than in 180 times in comparison with a direct fiber-waveguide coupling. Pros and cons of each configuration are discussed. Fabrication and characterisation results are reported.

Infrared nanoantenna couplers for plasmonic slot waveguide

A slot plasmonic waveguide is promising solution as a replacement of electrical interconnects in the future optical integrated circuits. In this contribution we consider a set of compact solutions for coupling the infrared light from free space to the plasmonic slot waveguide. We systematically study various designs: dipole antennas outside the waveguide, antennas inside the waveguide and bow-tie antennas in the slots.
Light modulation abilities of nanostructures

In the work we consider two new routes to impose control on the optical waveguides propagation. The first approach is based on the Kerr effect caused by the THz field, which strength is manifold times enhanced by the presence of a nanoslit in a metallic film surrounding the waveguide. The second approach utilizes the gain-core effect on plasmonics modes in metal-semiconductor-metal structures. Our simulations prove that it is quite reasonable to realize both control schemes experimentally.
Metamaterials modelling, fabrication and characterisation techniques

Metamaterials are artificially designed media that show averaged properties not yet encountered in nature. Among such properties, the possibility of obtaining optical magnetism and negative refraction are the ones mainly exploited but epsilon-near-zero and sub-unitary refraction index are also parameters that can be obtained. Such behaviour enables unprecedented applications.

Within this work, we will present various aspects of metamaterials research field that we deal with at our department. From the modelling part, various approaches for determining the value of the refractive index, permittivity and permeability can be used and we will present the ones developed and used at our group. Also, using transformation optics approach, one can determine the needed values for the permittivity and permeability in order to obtain the needed functionality.

Approaches in this area will be presented.

From the fabrication point of view, various 2D and 3D high resolution patterning techniques are used. The talk will describe the ones available within our group, starting with the classic UV-lithography and ending with more advanced ones, e.g. 2-photon-polymerisation and electron-beam lithography.

Measuring possibilities, both in the VIS/IR and well as in the THz regime, used for characterising the samples will be presented. The experimental challenges will be tackled during the talk.

General information
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Organisations: Department of Photonics Engineering, Plasmonics and Metamaterials, Teraherts Technologies and Biophotonics, National Institute for Optoelectronics, Bergische Universität Wuppertal
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Metamaterials modelling, fabrication, and characterisation techniques

Metamaterials are artificially designed media that show averaged properties not yet encountered in nature. Among such properties, the possibility of obtaining optical magnetism and negative refraction are the ones mainly exploited but epsilon-near-zero and sub-unitary refraction index are also parameters that can be obtained. Such behaviour enables unprecedented applications. Within this work, we will present various aspects of metamaterials research field that we deal with at our department. From the modelling part, we will present tour approach for determining the field enhancement in slits that have dimensions in the 10^4 times smaller than the incident wavelength. This huge difference makes it almost impossible for commercial software to handle thus analytical approached have to be employed. From the fabrication point of view, various 2D and 3D high resolution patterning techniques are used. The talk will describe the ones available within our group. We will present the electron-beam lithography approach for fabricating nano-antennae to be used in coupling of plasmonics waveguides to/from free space. Also, a 3D technique based on twophoton-polymerisation and isotropic metal deposition to fabricate metal-covered 3D photonic crystals will be discussed. From the measuring side we will present two THz based setups for obtaining material's characteristics, both in the low as well as in the high THz range, thus having the possibility of describing a material from 0.1 to 10THz. © 2012 SPIE.

General information
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Non-resonant terahertz field enhancement in periodically arranged nanoslits

We analyze ultra strong non-resonant field enhancement of THz field in periodic arrays of nanoslits cut in ultrathin metal films. The main feature of our approach is that the slit size and metal film thickness are several orders of magnitude smaller than the wavelength $\lambda$ of the impinging radiation. Two regimes of operation are found. First, when the grating period $P \ll \lambda$, frequency-independent enhancement is observed, accompanied by a very high transmission approaching unity. With high accuracy, this enhancement equals the ratio of $P$ to the slit width $w$. Second, when the grating period approaches the THz wavelength but before entering the Raleigh-Wood anomaly, the field enhancement in nanoslit stays close to that in a single isolated slit, i.e., the well-known inversefrequency dependence. Both regimes are non-resonant and thus extremely broadband for $P < \lambda$. The results are obtained by the microscopic Drude-Lorentz model taking into account retardation processes in the metal film and validated by the finite difference frequency domain method. We expect sensor and modulation applications of the predicted giant broadband field enhancement.

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Organisations: Department of Photonics Engineering, Plasmonics and Metamaterials, Terahertz Technologies and Biophotonics
Authors: Novitsky, A. (Intern), Ivinskaya, A. (Intern), Zalkovskij, M. (Intern), Malureanu, R. (Intern), Jepsen, P. U. (Intern), Lavrenenko, A. (Intern)
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Scopus rating (2009): SJR 1.518 SNIP 1.238
Web of Science (2009): Indexed yes
Optical waveguide mode control by nanoslit-enhanced terahertz field

In this Letter we propose a scheme providing control over an optical waveguide mode by a terahertz (THz) wave. The scheme is based on an optimization of the overlap between the optical waveguide mode and the THz field, with the THz field strength enhanced by the presence of a metallic nanoslit surrounding the waveguide. We find an optimum balance between the optical mode attenuation and Kerr-induced change in the propagation constant. The criterion for a π/2-cumulative phase shift, for instance for application in a Mach–Zehnder interferometer configuration, requires 10kV/cm THz field, which in turn is estimated to result in a nonlinear change of the refractive index in the waveguide of 0.001. Our simulations prove that it is quite reasonable to observe the effect experimentally.

General information
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Organisations: Department of Photonics Engineering, Plasmonics and Metamaterials, Terahertz Technologies and Biophotonics
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BFI (2010): BFI-level 2
Scopus rating (2010): SJR 2.669 SNIP 2.293
Web of Science (2010): Indexed yes
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Scopus rating (2009): SJR 3.167 SNIP 2.665
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Scopus rating (2008): SJR 3.408 SNIP 2.378
Web of Science (2008): Indexed yes
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Web of Science (2007): Indexed yes
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Web of Science (2006): Indexed yes
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Web of Science (2005): Indexed yes
Scopus rating (2004): SJR 3.521 SNIP 2.718
Web of Science (2004): Indexed yes
Scopus rating (2003): SJR 3.708 SNIP 2.573
Web of Science (2003): Indexed yes
Scopus rating (2002): SJR 3.702 SNIP 2.39
Web of Science (2002): Indexed yes
Scopus rating (2001): SJR 3.62 SNIP 2.244
Web of Science (2001): Indexed yes
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Passive THz metamaterials
In this work we present our activities in the fabrication and characterization of passive THz metamaterials. We use two fabrication processes to develop metamaterials either as free-standing metallic membranes or patterned metallic multi-layers on the substrates to achieve different functionalities. Our interest lies in metamaterials for a broad spectrum of linear properties in operations with THz waves, such as linear and circular polarizers, absorbers and devices with enhanced transmittivity, single layer dichroic and chiral systems. All the three steps (modelling, fabrication and characterization) will be discussed during the talk.

General information
State: Published
Organisations: Department of Photonics Engineering, Plasmonics and Metamaterials, Teraherts Technologies and Biophotonics, Bergische Universität Wuppertal, Fudan University
Authors: Lavrinenko, A. (Intern), Malureanu, R. (Intern), Zalkovskij, M. (Intern), Jepsen, P. U. (Intern), Novitsky, A. (Intern), Chigrin, D. N. (Ekstern), Kremers, C. (Ekstern), Song, Z. Y. (Ekstern), He, Q. (Ekstern), Zhou, L. (Ekstern)
Pages: 451-453
Publication date: 2012

Plasmonic modulator based on finite-thickness metal-semiconductormetal waveguide with gain core
We investigate plasmonic modulators with a gain material to be implemented as ultra-compact and ultra-fast active nanodevices in photonic integrated circuits. We analyze metal-semiconductor-metal (MSM) waveguides with InGaAsP-based active material layers as ultra-compact plasmonic modulators. The modulaion is achieved by changing the gain of the core that results in different transmittance through the waveguides. A MSM waveguide enables high field localization and therefore high modulation speed. Bulk semiconductor, quantum wells and quantum dots, arranged in either horizontal or vertical layout, are considered as the core of the MSM waveguide. Dependences on the waveguide core size and gain values of various active materials are studied. The designs consider also practical aspects like n- and p-doped layers and barriers in order to obtain results as close to reality. The effective propagation constants in the MSM waveguides are calculated numerically. Their changes in the switching process are considered as a figure of merit. We show that a MSM waveguide with electrical current control of the gain incorporates compactness and deep modulation along with a reasonable level of transmittance.

General information
State: Published
Organisations: Department of Photonics Engineering, Plasmonics and Metamaterials, Nanophotonic Devices
Authors: Babicheva, V. E. (Intern), Kulkova, I. V. (Intern), Malureanu, R. (Intern), Yvind, K. (Intern), Lavrinenko, A. V. (Intern)
Number of pages: 1
Publication date: 2012
Main Research Area: Technical/natural sciences
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**Plasmonic solutions for coupling and modulation**

We present our design results for efficient coupling and modulation in plasmonic structures. Fiber coupling to a plasmonic slot waveguide is significantly increased by a metallic nanoantenna with additional reflectors or by the configuration of several connected antennas. We also show that the plasmonic four-layer waveguide with patterned ITO layer can modulate light with higher transmission and the same modulation depth as a waveguide with a uniform ITO layer.

**General information**

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Organisations: Department of Photonics Engineering, Plasmonics and Metamaterials
Authors: Andryieuski, A. (Intern), Babicheva, V. (Intern), Malureanu, R. (Intern), Lavrinenko, A. (Intern)
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Invited talk.
Publication: Research - peer-review › Paper – Annual report year: 2012

**Ultrabroadband terahertz spectroscopy of chalcogenide glasses**

Chalcogenide glasses are receiving a lot of attention due to their unique optical properties. In this paper we study the optical properties of As2S3 and GaLaS glasses in a broad terahertz (THz) frequency range (0.2-18 THz). Complex dispersion behavior with drastic changes of refractive index and absorption coefficient is found for both glasses. We observe the breakdown of the universal power-law dependence of the absorption coefficient due to atomic vibrations observed at low THz frequencies in disordered materials, and see the transition to localized vibrational dynamics for the As2S3 compound at higher frequencies. In addition, As2S3 displays two transparency regions, at 7-8 THz and 12.2 THz, of potential interest for future nonlinear applications in the THz range.

**General information**

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Organisations: Plasmonics and Metamaterials, Department of Photonics Engineering, Terahertz Technologies and Biophotonics, National Institute for Optoelectronics
Authors: Zalkovskij, M. (Intern), Bisgaard, C. Z. (Intern), Novitsky, A. (Intern), Malureanu, R. (Intern), Savastru, D. (Ekstern), Popescu, A. (Ekstern), Jepsen, P. U. (Intern), Lavrinenko, A. (Intern)
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BFI (2015): BFI-level 2
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Web of Science (2015): Indexed yes
BFI (2014): BFI-level 2
Scopus rating (2014): SJR 1.799 SNIP 1.462 CiteScore 3.25
Web of Science (2014): Indexed yes
Ultrabroadband THz spectroscopic investigation of As$_2$S$_3$

We perform ultrabroadband THz spectroscopy of the dielectric function of arsenic trisulfide (As$_2$S$_3$). We observe the transition from universal scaling of the absorption at low frequencies to medium- and short-range-order at higher frequencies.
Wave-front-engineered grating mirrors for VCSELs

High-index-contrast grating mirrors featuring beam steering abilities for the transmitted beam as well as high reflectivity over a broad bandwidth are suggested. Gratings designed to provide control over the wave front of the transmitted beam are numerically investigated. The proposed structures are then fabricated for experimental characterization. The measurements performed show the beam steering ability of the suggested HCG designs and are also in good agreement with the theoretical predictions. General design rules to engineer these HCG structures for different applications are derived. These grating mirrors would have a significant impact on low cost laser sources fabrication, since a more efficient integration of optoelectronic modules can be achieved by avoiding expensive external lens systems.
A new approach to low loss photonic crystal waveguides

Photonic crystal waveguides allow ultra-compact realization of integrated optical components because they have high group index. However, they also induce significant losses in effect reducing the scope of their applications. We find that by increasing the photonic crystal hole to pitch ratio r/Λ to 0.388 a low loss transmission band is created below the traditional photonic crystal guiding band. Furthermore this low loss band has sharply defined cutoffs transmission edges for devices with a length of 50 μm or longer. Finite difference time domain and plane wave expansion simulations confirm the results and show that the sharpness of the cutoffs can be explained by the spectral shape of the guiding mode in the band diagram.

Cylindrical active coated nano-particles excited by electric and magnetic line sources

Cylindrical active coated nano-particles comprised of a silica nano-cylinder core covered with a plasmonic nano-shell are investigated with regard to their near- and far-field properties. The source of excitation is taken to be an electric or a magnetic line current, while three different plasmonic materials are employed for the nano-shells, namely silver, gold and copper.

Efficient and broadband nanoantenna coupler to plasmonic slot waveguide

General information
State: Published
Organisations: Plasmonics and Metamaterials, Department of Photonics Engineering, University of Southern Denmark
Authors: Andryieuski, A. (Intern), Malureanu, R. (Intern), Lavrinenko, A. (Intern), Volkov, V. S. (Ekstern), Radko, I. (Ekstern), Bozhevolnyi, S. I. (Ekstern)
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Enhanced broadband optical transmission in metallized woodpiles
We present an optimized isotropic metal deposition technique used for covering three-dimensional polymer structures with a 50 nm smooth silver layer. The technology allows fast and isotropic coating of complex 3D dielectric structures with thin silver layers. Transmission measurements of 3D metallized woodpiles reveal a new phenomenon of enhanced optical transmission in broadband range (up to 300 nm) in the near IR.

General information
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Organisations: Plasmonics and Metamaterials, Department of Photonics Engineering, Laser Zentrum Hannover e.V., Politecnico di Milano
Authors: Malureanu, R. (Intern), Alabastri, A. (Ekstern), Cheng, W. (Ekstern), Kiyan, R. (Ekstern), Chichkov, B. (Ekstern), Andryieuski, A. (Intern), Lavrinenko, A. (Intern)
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Fabrication and characterization of woodpile structures

In this paper we present the whole fabrication and characterization cycle for obtaining 3D metal-dielectric woodpile structures. The optical properties of these structures have been measured using different setups showing the need of considering e.g. border effects when planning their use in real-life devices. It was found that the behavior of the structures close to the edge is very different from the one in the middle. The existence of special features in the former spectra still needs to be completely understood and explained.

General information
High-index-contrast grating reflector with beam steering ability for the transmitted beam

High-index contrast grating mirrors providing wave front control of the transmitted light as well as high reflectivity over a broad bandwidth are suggested and both numerically and experimentally investigated. General design rules to engineer these structures for different applications are derived. Such grating mirrors would have a significant impact on low cost
laser fabrication, since a more efficient integration of optoelectronic modules can be achieved by avoiding expensive external lens systems.
Impact of the Excitation Source and Plasmonic Material on Cylindrical Active Coated Nano-Particles

Electromagnetic properties of cylindrical active coated nano-particles comprised of a silica nano-cylinder core layered with a plasmonic concentric nano-shell are investigated for potential nano-sensor applications. Particular attention is devoted to the near-field properties of these particles, as well as to their far-field radiation characteristics, in the presence of an electric or a magnetic line source. A constant frequency canonical gain model is used to account for the gain introduced in the dielectric part of the nano-particle, whereas three different plasmonic materials (silver, gold, and copper) are employed and compared for the nano-shell layers.
Low-loss transmission band in photonic crystal waveguides with sharp cutoff at a frequency below the bandgap

We present TE transmission measurements of photonic crystal waveguides with high hole radius to period ratio r/Λ=0.388. This geometry introduces a unique low loss transmission band in addition to the traditional PhC guiding band and very sharp transmission edges for devices with a length of 50 μm or longer. Finite difference time domain and plane wave expansion simulations confirm the results and show that the sharpness of the cutoffs can be explained by the spectral shape of the guiding mode in the band diagram.

General information
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Organisations: Plasmonics and Metamaterials, Department of Photonics Engineering, Aarhus University
Authors: Krüger, A. C. (Ekstern), Zhang, M. (Ekstern), Groothoff, N. (Ekstern), Malureanu, R. (Intern), Kristensen, M. (Ekstern)
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Microscopic model of the THz field enhancement in a metal nanoslit
We discuss the strong THz-field enhancement effect in a metal slit of dozens of nanometers sizes reported recently. Proposed simple microscopic model considers electric charges induced at the edges of the slit by a polarized incident wave. These charges contribute then to the field in the slit. The model is capable of explaining peculiarities of the field enhancement phenomenon such as an inverse frequency dependence of the enhancement factor. It provides closed-form expressions for the enhancement factor and field mapping inside the slit having only one fitting parameter. The model predicts influence of the slit shape on the field enhancement.
Modelling, fabrication and characterisation of THz fractal meta-materials

We present theoretical predictions, fabrication procedure and characterisation results of fractal metamaterials for the THz frequency range. The characterisation results match well the predicted response thus validating both the fabrication procedure as well as the simulation one. Such systems show the possibility of fabricating new THz devices like polarisers, polarising beam splitters etc. We set a goal to develop a method which is unambiguous but at the same time simple and straightforward. We assume that this can be done by observing the wave propagation inside a metamaterial slab thick enough to avoid transient effects. First, we formulated a retrieval method applicable to relatively thick slab when we can neglect the reflection from the rear interface [2]. Then phase and amplitude dependencies versus coordinates (cell number) allow the refractive index retrieving. Getting the input (Bloch) impedance from the reflection on the input interface serves to determine complex wave effective parameters. Extending the method further we developed the approach to determine both wave and material effective parameters through the Bloch-mode analysis [3]. The idea is to perform the Bloch mode expansion [4] of the field inside the metamaterial slab when it is illuminated with a plane wave incident from vacuum. Then we determine the effective refractive index from the propagation constant of the dominating (fundamental) Bloch mode. The Bloch and wave impedances are determined by definition as the proportionality coefficient between the electric and magnetic fields of the fundamental Bloch mode.

General information

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Organisations: Plasmonics and Metamaterials, Department of Photonics Engineering, Terahertz Technologies and Biophotonics, Fudan University
Authors: Xiao, S. (Ekstern), Zhou, L. (Ekstern), Malureanu, R. (Intern), Lavrinenko, A. (Intern), Cooke, D. (Intern), Jepsen, P. U. (Intern)
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Abstract_rma_ICNP2011_1_.pdf
Negative Index Materials and Plasmonic Antennas Based Nanocouplers
This thesis describes the development, design and fabrication of the nanocoupler that is a device coupling light from conventional optical fiber to the nanosize plasmonic slot waveguide. This device can decrease the coupling region to several micrometers providing compact interface between an optical fiber and future optical integrated circuit. Multiple nanocoupler possibilities are analyzed. Two realizations are investigated: negative index metamaterial and plasmonic nanoantenna based. The cubic symmetric negative index metamaterial Split cube in Cage and Split cube in Carcass designs for the telecom frequencies are proposed. It is shown that despite the exceptional bulkness (effective properties do not depend on the number of layers) and cubic symmetry the abovementioned designs exhibit strong spatial dispersion in the frequency range of interest. That prevents treating them as an isotropic negative index material. The wave propagation retrieval method for metamaterials with linear and circular eigenpolarizations and the field averaging of the restored Bloch mode method are proposed for metamaterials effective properties characterization. The methods are based on observation of the wave propagation in the metamaterial slab. The methods are unambiguous, simple, can be applied to lossy and lossless metamaterials with negative and positive refractive index, permittivity and permeability. The technology of silver nanometallization of complex 3D dielectric structures is developed. The metallization is based on silver reduction from the silver-ammonia complex with formaldehyde. Continuous and smooth silver layer can be deposited starting from 30 nm. The technology can be used for the complex photonic structures fabrication for the infrared frequencies. The coupling effects between metamaterials monolayers are investigated. It is shown that some metamaterials can be treated as homogeneous in the resonant frequency region, but some cannot at any value of the metamaterials period. The quantitative homogenization condition is formulated. Five types of the nanoantenna based couplers are developed: dipole antennas outside symmetric and asymmetric waveguide, antennas gratings, antennas inside waveguide and battle axe nanocoupler. It is shown that the usage of the side and top reflectors generally increases the power captured by the nanocoupler from the incident wave. The optimized geometrical parameters of the nanoantenna couplers are found out. The best performance is shown by the battle axe nanocoupler that has an antenna figure of merit equal to 1.8 μm² for five antenna periods. That is 90 times larger than antenna figure of merit for the waveguide without nanocoupler (0.02 μm²). The antenna nanocoupler fabrication technology is optimized. Plasmonic antennas nanocouplers are fabricated. Coupling to the plasmonic slot waveguide is experimentally demonstrated.

New Circular Fractal Sensors for Near-infrared Wavelengths

General information
State: Published
Organisations: Department of Photonics Engineering, Plasmonics and Metamaterials
Authors: Andryieuski, A. (Intern), Lavrinenko, A. (Intern), Malureanu, R. (Intern)
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Series: Progress in Electromagnetics Research Symposium
ISSN: 1559-9450
New fractal structures for frequencies close to the visible range
In this paper we present a new type of fractal resonator to be used in the red/NIR region of the spectra. The structure presents high-transmission band in 795-825nm range. The stop band is in the 683-731 nm range. Due to the huge difference in the spectra within such a short range, the structure can be used as an efficient sensor, both in transmission as well as in reflection. Thus, a variation of only 0.09 in the refraction index will for example change the structure’s behaviour from 90% reflection to 90% transmission. Such resonances lead to a sensitivity of 780 nm/RIU. Another advantage of this resonator is the independency of the incidence angle - in the spectral region of interest; the incidence angle has very little influence over the response.

General information
State: Published
Organisations: Plasmonics and Metamaterials, Department of Photonics Engineering, Politehnica University
Authors: Malureanu, R. (Intern), Sandru, A. (Ekstern), Andryieuski, A. (Intern), Lavrinenko, A. (Intern)
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Main Research Area: Technical/natural sciences
Conference: 5th International Congress on Advanced Electromagnetic Materials in Microwaves and Optics, Barcelona, Spain, 10/10/2011 - 10/10/2011
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Plasmonic nanoantenna based coupler for telecom range

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Organisations: Plasmonics and Metamaterials, Department of Photonics Engineering
Authors: Andryieuski, A. (Intern), Malureanu, R. (Intern), Lavrinenko, A. (Intern)
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Spherical active coated nano-particles – impact of the electric Hertzian dipole orientation
Spherical active coated nano-particles comprised of a silica nano-cylinder core covered with a plasmonic nano-shell are investigated with regard to their near- and far-field properties. The source of excitation is taken to be that of a tangential or
a radial electric Hertizan dipole while three different plasmonic materials are employed for the nano-shells, namely silver, gold and copper.

Transmission and Reflection Spectroscopy of Terahertz Fractal Metamaterials

Two-Dimensional Fractal Metamaterials for Applications in THz

The concept of metamaterials (MTMs) is acknowledged for providing new horizons for controlling electromagnetic radiations thus their use in frequency ranges otherwise difficult to manage (e.g. THz radiation) broadens our possibility to better understand our world as well as opens the path for new applications. THz radiation can be employed for various purposes, among them the study of vibrations in biological molecules, motion of electrons in semiconductors and propagation of acoustic shock waves in crystals. We propose here a new THz fractal MTM design that shows very high transmission in the desired frequency range as well as a clear differentiation between one polarisation and another. Based on theoretical predictions we fabricated and measured a fractal based THz metamaterial that shows more than 60% field transmission at around 1 THz for TE polarized light while the TM waves have almost 80% field transmission peak at 0.6 THz. One of the main characteristics of this design is its tunability by design: by simply changing the length of the fractal elements one can choose the operating frequency window. The modelling, fabrication and characterisation results will be presented in this paper.
Ultrabroadband THz spectroscopy of disordered materials

We perform THz spectroscopic investigations of the dielectric function of disordered materials in the THz region. Specifically, we consider amorphous materials and perform ultrabroadband THz spectroscopy of chalcogenide glasses where we observe the transition from universal scaling of the absorption at low frequencies to medium-range order and local order at higher frequencies.

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Organisations: Department of Photonics Engineering, Plasmonics and Metamaterials, Terahertz Technologies and Biophotonics, National Institute for Optoelectronics
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Electronic versions: disordered_solids.pdf
Links: http://www.ile.osaka-u.ac.jp/research/THP/TeraNano/
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Vertical sidewall roughness measured by AFM and SEM

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Wave impedance retrieving via Bloch modes analysis

The main bottleneck in the restoration of electromagnetic effective parameters is connected to the impedance retrieving. The S-parameters method gives the input (Bloch) impedance, which, being then used for permittivity and permeability determination, causes some fundamental physics principles violation, like antiresonance behaviour with Im(\(\varepsilon\)) < 0, Im(\(\mu\)) < 0. We employ the Bloch mode analysis of periodic metamaterials to extract the dominating (fundamental) Bloch mode. Then it is possible to determine the Bloch and wave impedances by the surface and volume averaging of the electromagnetic field of the Bloch mode, respectively. Case studies prove that our approach can determine material and wave effective parameters of lossy and lossless metamaterials. In some examples when the passivity is violated we made
further analysis and showed that this is due to the failure of concept of impedance retrieving through the volume averaging.

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Organisations: Plasmonics and Metamaterials, Department of Photonics Engineering, Australian National University
Authors: Andryieuski, A. (Intern), Ha, S. (Ekstern), Sukhorukov, A. (Ekstern), Malureanu, R. (Intern), Kivshar, Y. (Ekstern), Lavrinenko, A. (Intern)
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Publication: Research - peer-review › Article in proceedings – Annual report year: 2011

**Wave propagation in metamaterials and effective parameters retrieving**
Metamaterials, as a class of artificial materials with extraordinary electromagnetic properties, require reliable methods of their properties determination. The vast majority of researchers and engineers apply the simple S-parameters based method [1]. Its disadvantage is the ambiguity of the determined effective parameters and applicability to thin slabs only. The other methods based, for example, on the eigenfunctions calculations [Menzel], or analytical calculations [Simovski] require advanced skills either in numerical methods and programming or in analytical derivations and maybe considered as handsome for implementation. We set a goal to develop a method which is unambiguous but at the same time simple and straightforward. We assume that this can be done by observing the wave propagation inside a metamaterial slab thick enough to avoid transient effects. First, we formulated a retrieval method applicable to relatively thick slab when we can neglect the reflection from the rear interface [2]. Then phase and amplitude dependencies versus coordinates (cell number) allow the refractive index retrieving. Getting the input (Bloch) impedance from the reflection on the input interface serves to determine complex wave effective parameters. Extending the method further we developed the approach to determine both wave and material effective parameters through the Bloch-mode analysis [3]. The idea is to perform the Bloch mode expansion [4] of the field inside the metamaterial slab when it is illuminated with a plane wave incident from vacuum. Then we determine the effective refractive index from the propagation constant of the dominating (fundamental)
Bloch mode. The Bloch and wave impedances are determined by definition as the proportionality coefficient between the electric and magnetic fields of the fundamental Bloch mode.

Wave propagation in structured materials as a platform for effective parameters retrieving

One of the most convenient ways to describe metamaterial (MM) media is by employing effective parameters (EPs), provided that they can be introduced. Generally, in literature two types of EPs are considered: wave and material parameters. The former EPs may be derived from the reflection/transmission spectra at a fixed incident angle. However, for a complete description of MM properties, material EPs should be introduced. Up to now, a large variety of retrieval methods has been suggested. The simplest and most used definitely is the S-parameters method also referred to as the Nicholson-Ross-Weir (NRW) method. The majority of the retrieving methods are either simple but give wave (or nonlocal) EPs, or they provide material (local) parameters but at the cost of complexity in realization and sometimes with restricted applicability. The universal procedure of EPs retrieval have not been fully established yet. In this contribution, we present an overview of our activity in EPs retrieving based on observation of wave propagation phenomena in thick (multilayer) MMs. We put a goal to develop a method which is unambiguous, but at the same time simple and straightforward. The idea is that thick enough MM slab can be considered as a semi-infinite medium. Modelling the one-directional (forward) propagation of the wave inside a metamaterial slab thick enough to avoid transition layers effects and reflection from the rear interface we are able to restore complex refractive index. Getting the input (Bloch) impedance from the reflection at the input interface serves to determine complex wave effective parameters. The method was successfully extended on chiral media with circular polarized eigenwaves. Elaborating the approach we aim to determine both the wave and material EPs in periodic MMs via utilization of the Bloch-mode analysis. The idea is to perform the Bloch mode expansion of the field inside the metamaterial slab when it is illuminated with a plane wave incident from vacuum. Then we determine the effective refractive index from the propagation constant of the dominating (fundamental) Bloch mode. The Bloch and wave impedances are determined by definition as the proportionality coefficient between electric and magnetic fields of the fundamental Bloch mode volume or surface averaged over the unit cell. The ratio of the surface averaged fields provides the value of the Bloch impedance and, respectively, enables the retrieval of wave EPs. The volume averaging provides the wave impedance, which is needed for the retrieval of the materials parameters. The main advantage of our method is its simple numerical realization. The first part of the method involves the extraction of the dominating (fundamental) Bloch modes from the simulation data of the field distribution in several unit cells. The retrieval procedure is performed within a single computational cycle, after exporting fields directly from Maxwell's equations solver. In this presentation we analyze the following examples: (1) homogeneous slab under two cases: lossless and Lorentz dispersion in permittivity and permeability; (2) a set of nanospheres with plasmonic resonances; (3) split cubes metamaterial that possesses magnetic resonance and negative permeability; (4) a wire medium with negative permittivity; (5) negative refractive index fishnet structure; and (6) split-cube-in-carcass structure. In the last two cases volume-averaged fields lead to negative real part of the impedance, the fact that signals on violation of the direction of the Poynting vector for outward wave propagation. For deeper understanding we focus on the Bloch modes contributions into the total field structure and in the flux density, which can differ considerably in the resonant part of the spectrum. The analysis of the contributions will be reported at the symposium too.
Wave propagation phenomena in metamaterials for retrieving of effective parameters

In the talk we give an overview of the developed restoration procedures and discuss their pros and cons in connection of assigning effective parameters (EP) to metamaterials (MMs). There are plenty of notorious physical phenomena preserving the unambiguous retrieving of EP, like strong coupling between constitutive elements, multipoles resonances, multimode or photonic crystal (diffraction type) regimes. There are also technical limitations of the retrieval methods connected with very strong losses, branching ambiguity, convergence to bulk parameters, etc. Moreover, most of the simple methods reveal so-called wave effective parameters, assigned for particular light propagation direction in numerical or real experiments. Therefore, finding the EP is a tricky problem, which still requires a lot of contribution to get deeper insight in it. We report on our advances in restoration MMs EP taking into account propagation of eigen-waves in multilayered structures (thicknesses 10-100 unit cells). Thus, the question of parameters convergence is naturally resolved in our approach. The method has been tested on complex three-dimensional structures like a split-cube-in-carcass and with circular polarized waves on chiral MMs [1, 2]. Elaborating our approach the new method has been established, where the unit-cell volume and face field averaging procedures define wave and input (Bloch) impedances correspondingly. The first part of the method involves the extraction of the dominating (fundamental) Bloch modes from the simulation data of the field distribution in several unit cells [3]. Then, we explicitly perform either volume or surface averaging of the electric and magnetic fields of the dominant forward-propagating Bloch mode over the unit cell. The ratio of the surface averaged fields provides the value of the Bloch impedance and, respectively, enables the retrieval of wave EPs. The volume averaging of fields of forward propagating fundamental Bloch wave provides the wave impedance, which is needed for the retrieval of the materials parameters. The method is illustrated with several examples.

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Authors: Andryieuski, A. (Intern), Malureanu, R. (Intern), Ha, S. (Ekstern), Sukhorukov, A. A. (Ekstern), Kivshar, Y. S. (Ekstern), Lavrinenko, A. (Intern)
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1x3 beam splitter based on self-imaging phenomena in air-slab photonic crystal waveguides
A 1 x 3 beam splitter using multi-mode interference based on self-imaging is demonstrated theoretically and experimentally in PhCWs. The total transmission of the 1 x 3 splitter is almost equal to the corresponding length of W1 PhCW. The input power is distributed equally between the output ports within 1 dB from 1541 nm to 1552 nm.

General information
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Organisations: Plasmonics and Metamaterials, Department of Photonics Engineering, Aarhus University
Authors: Zhang, M. (Ekstern), Kristensen, M. (Ekstern), Malureanu, R. (Intern), Krüger, A. C. (Ekstern)
Publication date: 2010
Main Research Area: Technical/natural sciences
Source: orbit
1x3 beam splitter for TE polarization based on self-imaging phenomena in photonic crystal waveguides

Based on inspiration from multi-mode interference self-imaging and theoretical FDTD simulations, a 1x3 beam splitter was designed, fabricated and characterized. Measurements show that for TE-polarized incident light the power is distributed equally between the output ports within 1dB in the range from 1541nm to 1552nm, and the total transmission of the 1x3 splitter is equal to the corresponding length of a single-line-defect PhCW within the measurement uncertainty.

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Organisations: Plasmonics and Metamaterials, Department of Photonics Engineering, Aarhus University
Authors: Zhang, M. (Ekstern), Malureanu, R. (Intern), Krüger, A. C. (Ekstern), Kristensen, M. (Ekstern)
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Web of Science (2017): Indexed yes
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Scopus rating (2016): CiteScore 3.48 SJR 1.487 SNIP 1.589
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 2
Scopus rating (2015): SJR 1.976 SNIP 1.755 CiteScore 3.78
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 2
Scopus rating (2014): SJR 2.349 SNIP 2.166 CiteScore 4.18
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 2
Scopus rating (2013): SJR 2.358 SNIP 2.226 CiteScore 4.38
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 2
Scopus rating (2012): SJR 2.587 SNIP 2.145 CiteScore 3.85
ISI indexed (2012): ISI indexed yes
Web of Science (2012): Indexed yes
BFI (2011): BFI-level 2
Scopus rating (2011): SJR 2.579 SNIP 2.606 CiteScore 4.04
ISI indexed (2011): ISI indexed yes
Web of Science (2011): Indexed yes
BFI (2010): BFI-level 2
Scopus rating (2010): SJR 2.943 SNIP 2.466
Web of Science (2010): Indexed yes
BFI (2009): BFI-level 2
Scopus rating (2009): SJR 3.092 SNIP 2.669
Web of Science (2009): Indexed yes
BFI (2008): BFI-level 2
Scopus rating (2008): SJR 3.195 SNIP 2.393
Web of Science (2008): Indexed yes
Scopus rating (2007): SJR 3.27 SNIP 2.032
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Chiral metamaterials characterisation using the wave propagation retrieval method

In this presentation we extend the wave propagation method for the retrieval of the effective properties to the case of chiral metamaterials with circularly polarised eigenwaves. The method is unambiguous, simple and provides bulk effective parameters. Advantages and constraints are discussed.
Controlled Ag electroless deposition in bulk structures with complex three-dimensional profiles

In this work we show the possibility of controlled deposition of a nanometer-sized silver layer on three-dimensional 3D structures. The deposition takes place in liquid environment, allowing for an easy and fast processing with intrinsically isotropic characteristics. The obtained layers are of high uniformity, having an average roughness of about 4 nm. The characterization of the metal deposition is done using both the scanning electron microscopy technique as well as by atomic force microscope measurements. The electroless technique can be easily implemented, providing the effective and reliable metal deposition for fabrication of 3D samples in the broad range of plasmonics and photonics applications.
Enhanced broadband optical transmission in metallized woodpiles

We present an optimized isotropic metal deposition technique used for coating three-dimensional polymer structures with a 50nm smooth silver layer. The technology allows fast isotropic coating of complex 3D dielectric structures with thin silver layers. Transmission measurements of 3D metallized woodpiles reveal a new phenomenon of enhanced optical transmission in broadband range (up to 300 nm) in the near IR.

General information
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Organisations: Plasmonics and Metamaterials, Department of Photonics Engineering, Laser Zentrum Hannover e.V., Politecnico di Milano
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Fractal THz metamaterials: design, fabrication and characterisation
The concept of metamaterials (MTMs) is acknowledged for providing new horizons for controlling electromagnetic radiations thus their use in frequency ranges otherwise difficult to manage (e.g. THz radiation) broadens our possibility to better understand our world as well as opens the path for new applications. THz radiation can be employed for various purposes, among them the study of vibrations in biological molecules, motion of electrons in semiconductors and propagation of acoustic shock waves in crystals. We propose here a new THz fractal MTM design that shows very high transmission in the desired frequency range as well as a clear differentiation between one polarisation and another. Based on theoretical predictions we fabricated and measured a fractal based THz metamaterial that shows more than 60% field transmission at around 1THz for TE polarized light while the TM waves have almost 80% field transmission peak at 0.6THz. One of the main characteristics of this design is its tunability by design: by simply changing the length of the fractal elements one can choose the operating frequency window. The modelling, fabrication and characterisation results will be presented in this paper. Due to the long wavelength of THz radiation, the resolution requirements for fabrication of metamaterials are within the optical lithography range. However, the high aspect ratio of such structures as well as the substrate thickness pose challenges in the fabrication process. The measurements were made using terahertz time domain spectroscopy (THz-TDS) that allows us to obtain both the amplitude and phase of the transmission function. The experimental results are in very good agreement with theoretical calculations based on finite-difference time-domain simulations.

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Organisations: Plasmonics and Metamaterials, Department of Photonics Engineering, Terahertz Technologies and Biophotonics, Structured Electromagnetic Materials, Fudan University
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Scopus rating (2016): CiteScore 0.42 SNIP 0.245
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BFI (2013): BFI-level 1
Scopus rating (2013): SJR 0.2 SNIP 0.259 CiteScore 0.26
ISI indexed (2013): ISI indexed no
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 1
Scopus rating (2012): SJR 0.194 SNIP 0.243 CiteScore 0.27
ISI indexed (2012): ISI indexed no
Web of Science (2012): Indexed yes
BFI (2011): BFI-level 1
Scopus rating (2011): SJR 0.197 SNIP 0.264 CiteScore 0.31
ISI indexed (2011): ISI indexed no
BFI (2010): BFI-level 1
Scopus rating (2010): SJR 0.208 SNIP 0.241
Web of Science (2010): Indexed yes
BFI (2009): BFI-level 1
High symmetry versus optical isotropy of a negative-index metamaterial

Optically isotropic metamaterials (MMs) are required for the implementation of subwavelength imaging systems. At first glance, one would expect that their design should be based on unit cells exhibiting a cubic symmetry being the highest crystal symmetry. It is anticipated that this is a sufficient condition since it is usually assumed that light does not resolve the spatial details of MM but experiences the properties of an effective medium, which is then optically isotropic. In this work we challenge this assumption by analyzing the isofrequency surfaces of the dispersion relation of the split cube in carcass negative index MM. We show that this MM is basically optically isotropic but not in the spectral domain where it exhibits negative refraction. The primary goal of this contribution is to introduce a tool that allows to probe a MM against optical isotropy.
Homogenization of metamaterials: Parameters retrieval methods and intrinsic problems

Metamaterials (MTMs) claim a lot of attention worldwide. Description of the MTMs in terms of effective parameters is a simple and useful tool for characterisation of their electromagnetic properties. So a reliable effective parameters restoration method is on demand. In this paper we report about our activity and advances in the effective properties of metamaterials characterization. We present here the wave propagation retrieval method in two formulations: for MTMs with linear eigenwaves and for chiral MTMs with circular eigenwaves. The advantages and constraints of the method are noted. The case studies of the negative-index, ultra-high refractive index and chiral MTMs validate the method.
Homogenization of resonant chiral metamaterials

Homogenization of metamaterials is a crucial issue as it allows to describe their optical response in terms of effective wave parameters as, e.g., propagation constants. In this paper we consider the possible homogenization of chiral metamaterials. We show that for meta-atoms of a certain size a critical density exists above which increasing coupling between neighboring meta-atoms prevails a reasonable homogenization. On the contrary, a dilution in excess will induce features reminiscent to photonic crystals likewise prevailing a homogenization. Based on Bloch mode dispersion we introduce an analytical criterion for performing the homogenization and a tool to predict the homogenization limit. We show that strong coupling between meta-atoms of chiral metamaterials may prevent their homogenization at all.
Is it possible to homogenize resonant chiral metamaterials?

Homogenization of metamaterials is very important as it makes possible description in terms of effective parameters. In this contribution we consider the homogenization of chiral metamaterials. We show that for some metamaterials there is an optimal meta-atom size which depends on the coupling between meta-atoms. We introduce numerical criterion of homogeneity on the basis of the Bloch modes dispersion diagram calculation and a tool to predict the homogeneity limit. We show that some metamaterials with strong coupling between meta-atoms cannot be considered as homogeneous at all.

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Isotropic optical metamaterials

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Organisations: Department of Photonics Engineering, Plasmonics and Metamaterials, Friedrich-Schiller-Universität Jena
Authors: Lederer, F. (Ekstern), Rockstuhl, C. (Ekstern), Menzel, C. (Ekstern), Paul, T. (Ekstern), Andryieuski, A. (Intern), Malureanu, R. (Intern), Lavrinenko, A. (Intern)
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Isotropic optical metamaterials
Metamaterial imaging applications require optical isotropy. We show that highly symmetric unit cells do not necessarily exhibit this property. We prove that the dispersion relation can be tailored using a supercell metamaterial. Such metamaterial exhibits an isotropic negative index close to -1. Its potential for image formation is discussed.

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Nearly zero transmission through periodically modulated ultrathin metal films
Transmission of light through an optically ultrathin metal film with a thickness comparable to its skin depth is significant. We demonstrate experimentally nearly-zero transmission of light through a film periodically modulated by a one-dimensional array of subwavelength slits. The suppressed optical transmission is due to the excitation of surface plasmon polaritons and the zero-transmission phenomenon is strongly dependent on the polarization of the incident wave.

General information
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Optical isotropic negative index metamaterials
Towards isotropic metamaterials, we analyze isofrequency surfaces of the dispersion relation of high symmetry metamaterials and show that they are optically not isotropic. We achieve instead isotropic metamaterials that consist of carefully designed multiple layers.

Optimisation of the electroless metal deposition technique for use in photonics
Even if the first approach toward metamaterials was made more than 40 years ago [1] the topic was not considered for practical applications until 2000 due to the lack of natural materials with tuneable magnetic interaction with electromagnetic waves. In 1999 the first engineered metamaterial was suggested [2] and, one year later, it was characterised [3] thus starting the research interest in this field. Since then, the operating wavelength decreased from microwave to visible frequencies, the newest results showing negative refraction in the yellow region of the spectrum [4]. With all the progress made in the last years, there is still a long way until practical implementation into everyday devices. One of the main bottlenecks, from the fabrication point of view, is the necessity for depositing silver on complex 3D structures. To our knowledge, the best result so far, was obtained using plasma enhanced chemical vapour deposition (PECVD) technique [5]. Even if the results are promising, the parameter space of such technique is huge thus making it almost impossible to avoid the local optimum points. In this work we present an optimised technique for 3D deposition of metals. Our technique is based on the well known Tollen’s test for detecting the presence of aldehyde groups inside a solution [6]. By optimising the concentration and the ratio of the chemicals involved, one can obtain very smooth and thin Ag layers (see figure 1a). In the same time, since the reaction takes place in solution, it is by definition isotropic and thus suitable for depositing the metal on complex structures (see figure 1b).

Web of Science (2002): Indexed yes
Scopus rating (2001): SJR 4.111 SNIP 2.212
Web of Science (2001): Indexed yes
Scopus rating (2000): SJR 4.277 SNIP 2.013
Web of Science (2000): Indexed yes
Scopus rating (1999): SJR 4.35 SNIP 2.11
Original language: English
Surface plasmons, Optical films, Light polarisation, Polaritons, Metallic thin films, Optical arrays, Light transmission
DOIs:
10.1063/1.3481397
Source: orbit
Source-ID: 266579
Publication: Research - peer-review › Journal article – Annual report year: 2010
Transmission and reflection properties of terahertz fractal metamaterials
We use THz time-domain spectroscopy to investigate transmission and reflection properties of metallic fractal metamaterial structures. We observe loss of free-space energy at certain resonance frequencies, indicating excitation of surface modes of the metamaterial.

General information
State: Published
Organisations: Plasmonics and Metamaterials, Department of Photonics Engineering, Terahertz Technologies and Biophotonics, Fudan University
Authors: Malureanu, R. (Intern), Lavrinenko, A. (Intern), Cooke, D. (Intern), Jepsen, P. U. (Intern), Xiao, S. (Ekstern), Zhou, L. (Ekstern)
Pages: 1-2
Publication date: 2010

Host publication information
Title of host publication: 2010 Conference on Lasers and Electro-Optics (CLEO) and Quantum Electronics and Laser Science Conference (QELS)
Publisher: IEEE
ISBN (Print): 978-1-55752-890-2
Main Research Area: Technical/natural sciences
Conference: Conference on Lasers and Electro-Optics (CLEO)/International Quantum Electronics Conference (IQEC), San Jose, CA, United States, 16/05/2010 - 16/05/2010
Electronic versions: Malureanu.pdf

Bibliographical note
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Wave propagation retrieval method for chiral metamaterials
In this paper we present the wave propagation method for the retrieving of effective properties of media with circularly polarized eigenwaves, in particular for chiral metamaterials. The method is applied for thick slabs and provides bulk effective parameters. Its strong sides are the absence of artificial branches of the refractive index and simplicity in implementation. We prove the validity of the method on three case studies of homogeneous magnetized plasma, bi-cross and U-shaped metamaterials.

General information
State: Published
Organisations: Plasmonics and Metamaterials, Department of Photonics Engineering
Authors: Andryieuski, A. (Intern), Malureanu, R. (Intern), Lavrinenko, A. (Intern)
Pages: 15498-15503
Publication date: 2010
Main Research Area: Technical/natural sciences

Publication information
Journal: Optics Express
Volume: 18
Issue number: 15
ISSN (Print): 1094-4087
Ratings:
BFI (2017): BFI-level 2
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 2
Scopus rating (2016): CiteScore 3.48 SJR 1.487 SNIP 1.589
3D geometrically isotropic metamaterial for telecom wavelengths

We present a new design for a unit cell with the cubic symmetry and sizes less than one sixth of the vacuum wavelength possessing a negative refractive index in the IR region. The main challenges in designing and fabricating metamaterials nowadays are in obtaining isotropic electric and magnetic responses keeping in the same time the cell dimensions within the effective medium approximation. Several approaches have been made to develop such a structure in the microwave region [1, 2], nevertheless, there is still a lack of structures to be used in the IR and visible diapasons. Since the dimension of the unit cell is not infinitely small, certain geometrical constraints have to be fulfilled to obtain an isotropic response of the material [3]. These conditions and the metal behaviour close to the plasma frequency increase the design complexity. Our unit cell is composed of two main parts. The first part generates the electric response, thus providing the negative real part of permittivity in the desired spectral range. The usual way is to utilize a set of metallic wires, so called diluted metal that exhibits a Drude-like behaviour. Our study shows that this behaviour is obtainable if the wires are arranged in a cage-like structure. For the magnetic response we use metallic plates forming an open cube located inside the “cage”. For this topology the plates can be thought of as capacitors in a resonant LC circuit [4]. By adjusting the resonant circuit frequency in the IR range a double negative response is obtained in a certain bandwidth. The proposed unit cell has the cubic point group of symmetry and being repeatedly placed in space can effectively reveal isotropic optical properties. We use the CST commercial software to characterise the “cube-in-cage” structure. Reflection and transmission spectra are shown in Fig.1a. The effective refractive index is retrieved accordingly to the standard algorithm [5] (see Fig.1b). After several cycles of naïve optimizations, the refractive index reaches -2.4 at 1.55μm (ca. 192.5THz). The maximum FOM in the band, where Re(n) <0 is 2.4 at 1.54μm (ca. 195.2THz). At this wavelength the refraction index is equal to -1.44. These values together with the effective cubic symmetry of the unit cell entitle us to assume the high potential of the suggested design as a constitutive block for an isotropic, relatively low-loss, metamaterial in the near IR region.

General information
State: Published
Organisations: Plasmonics and Metamaterials, Department of Photonics Engineering
Authors: Malureanu, R. (Intern), Andryieuski, A. (Intern), Lavrinenko, A. (Intern)
Pages: TUE4F.16
Publication date: 2009

Host publication information
Title of host publication: Proceedings, NANOMETA
Main Research Area: Technical/natural sciences
Conference: 2nd European Topical Meeting on Nanophotonics and Metamaterials, Seefeld, Austria, 05/01/2009 - 05/01/2009
Source: orbit
Source-ID: 233888
Publication: Research - peer-review › Article in proceedings – Annual report year: 2009

Bulk isotropic negative-index material design for infrared

Responding to the strong call for isotropic bulk negative index material we propose a Split Cube in Car-cass design. It shows negative refractive index -1.5, figure-of-merit 2 and transmittivity 30% for one layer at the telecommunication wavelength 1.6 μm. Effective parameters converge fast with a number of layers. The effective parameters retrieval method based on the wave propagation simulation is proposed and compared with standard procedure. It is shown that standard restoration method while used for the S-parameters spectra calculations with pulse sources excitation can contain an error connected to the transient period of the resonant circuits.

General information
State: Published
Organisations: Department of Photonics Engineering
Authors: Andryieuski, A. (Intern), Malureanu, R. (Intern), Lavrinenko, A. (Intern)
Publication date: 2009

Bulk metamaterials: Design, fabrication and characterization: [invited]

Bulk metamaterials claim a lot of attention worldwide. We report about our activity and advances in design, fabrication and characterization of metal-dielectric composites with three-dimensional lattices. The nomenclature of designs exhibiting
negative index behaviour in the near infrared includes the generic family of so-called nested structures. Such designs allow keeping the cubic symmetry of the unit cell along with the electric and magnetic responses showed by different parts in separate. For extraction of effective parameters we employ homemade wave propagation retrieving method free from ambiguity generic to the standard S-parameters retrieval method. Accurateness of the method is highlighted by a set of numerical checks. To fabricate smooth metal three-dimensional structures we develop an electroless chemical technique. We present the results of silver deposition on the surface of a 30-layers-thick polymer woodpile photonic crystal. Characterization of such samples before and after metal deposition in the 700 nm - 1700 nm range exposes some unpredictable features like an enhanced broadband transmission, which still waits to be explained.

General information
State: Published
Organisations: Department of Photonics Engineering, Plasmonics and Metamaterials
Authors: Andryieuski, A. (Intern), Malureanu, R. (Intern), Alabastri, A. (Ekstern), Lavrinenko, A. (Intern)
Pages: 1-5
Publication date: 2009

Host publication information
Title of host publication: 3rd ICTON Mediterranean Winter Conference, 2009. ICTON-MW 2009
Publisher: IEEE
ISBN (Print): 978-1-4244-5745-8
Main Research Area: Technical/natural sciences
Conference: 11th International Conference on Transparent Optical Networks, Azores, Portugal, 28/06/2009 - 28/06/2009
Electronic versions:
Hansen.pdf
DOIs:
10.1109/ICTONMW.2009.5385647

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Source: orbit
Source-ID: 254201
Publication: Research - peer-review › Article in proceedings – Annual report year: 2009

Design and fabrication activity towards 3D negative refraction index materials in the IR region
In this paper we present a new 3D isotropic structure that allows obtaining negative refraction index in the telecom wavelength as well as first fabrication efforts towards obtaining such structures.

General information
State: Published
Organisations: Plasmonics and Metamaterials, Department of Photonics Engineering
Authors: Malureanu, R. (Intern), Andryieuski, A. (Intern), Lavrinenko, A. (Intern)
Pages: session 4, presentation 4
Publication date: 2009

Host publication information
Title of host publication: Proceedings, ETOPIM
Main Research Area: Technical/natural sciences
Source: orbit
Source-ID: 246143
Publication: Research - peer-review › Article in proceedings – Annual report year: 2009

Design of a three-dimensional metamaterial exhibiting isotropic properties in the near infrared range

General information
State: Published
Organisations: Plasmonics and Metamaterials, Department of Photonics Engineering
Authors: Andryieuski, A. (Intern), Malureanu, R. (Intern), Lavrinenko, A. (Intern)
Publication date: 2009
Event: Abstract from 25th Progress In Electromagnetics Research Symposium, Moscow, Russian Federation.
Main Research Area: Technical/natural sciences
Source: orbit
Isotropic metal deposition technique for metamaterials fabrication

In this work we will present the first steps taken towards isotropic deposition of thin metallic layers on dielectric substrates. The deposition takes place in aqueous environment thus making it both cheap and easy to be implemented.

General information
State: Published
Organisations: Plasmonics and Metamaterials, Department of Photonics Engineering
Authors: Malureanu, R. (Intern), Andryieuski, A. (Intern), Lavrinenko, A. (Intern)
Publication date: 2009

Host publication information
Title of host publication: Abstracts, Danish Physical Society - Nordic Meeting
Main Research Area: Technical/natural sciences
Conference: Danish Physical Society - Nordic Meeting, Copenhagen, Denmark, 16/06/2009 - 16/06/2009
Source: orbit
Source-ID: 245993
Publication: Research - peer-review › Article in proceedings – Annual report year: 2009

Nested structures approach for bulk 3D negative index materials: [invited]

We propose a generic conceptual idea to obtain bulk 3D negative index metamaterials, which exhibit isotropic properties. The design is based on the nested structures approach, when one element providing magnetic response is inserted into another design with negative dielectric constant. Both constitutive elements possess cubic symmetry, thus we preserve it for the whole unit cell. The concept can be applied for any frequencies; however, we are targeting optical and THz ranges. We report on numerical characterization of two particular designs, called as "split-cube-in-cage" and "split-cube-in-carcass", revealing negative index behaviour. Two approaches are applied – effective parameters approximation and phenomenological one, showing excellent correlation in results. The designs show good results in isotropy of effective properties and their convergence with the thickness of a sample. Apart from design and numerical analysis progress in vertical layers metal deposition is also addressed in the presentation.

General information
State: Published
Organisations: Department of Photonics Engineering, Plasmonics and Metamaterials
Authors: Andryieuski, A. (Intern), Malureanu, R. (Intern), Lavrinenko, A. (Intern)
Number of pages: 4
Pages: Th.A1.2
Publication date: 2009

Host publication information
Title of host publication: Proceedings, ICTON
Publisher: IEEE
ISBN (Print): 978-1-4244-4825-8
Main Research Area: Technical/natural sciences
Conference: 11th International Conference on Transparent Optical Networks, Azores, Portugal, 28/06/2009 - 28/06/2009
Electronic versions:
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DOIs:
10.1109/ICTON.2009.5185296

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Source: orbit
Source-ID: 246587
Publication: Research - peer-review › Article in proceedings – Annual report year: 2009

Nested structures approach in designing an isotropic negative-index material for infrared

We propose a new generic approach for designing isotropic metamaterial with nested cubic structures. As an example, a three-dimensional isotropic unit cell design "Split Cube in Cage" (SCiC) is shown to exhibit an effective negative refractive index on infrared wavelengths. We report on the refractive index reaching -2.3 and the figure of merit as high as 2.7. The structure exhibits potential for application as a building block of isotropic negative-index materials.
Simplified 3D isotropic structure for negative index materials in the IR regime

General information
State: Published
Organisations: Plasmonics and Metamaterials, Department of Photonics Engineering
Authors: Andryieuski, A. (Intern), Malureanu, R. (Intern), Lavrinenko, A. (Intern)
Pages: 09003
Publication date: 2009
Main Research Area: Technical/natural sciences

Publication information
Volume: 4
ISSN (Print): 1990-2573
Ratings:
BFI (2017): BFI-level 1
Web of Science (2017): Indexed Yes
BFI (2016): BFI-level 1
Scopus rating (2016): SJR 0.524 SNIP 0.603 CiteScore 1.34
BFI (2015): BFI-level 1
Scopus rating (2015): SJR 0.565 SNIP 0.655 CiteScore 1.26
BFI (2014): BFI-level 1
Scopus rating (2014): SJR 0.733 SNIP 0.935 CiteScore 1.42
BFI (2013): BFI-level 1
Scopus rating (2013): SJR 0.468 SNIP 0.748 CiteScore 0.95
ISI indexed (2013): ISI indexed yes
BFI (2012): BFI-level 1
Scopus rating (2012): SJR 0.476 SNIP 0.569 CiteScore 0.71
ISI indexed (2012): ISI indexed yes
BFI (2011): BFI-level 1
Scopus rating (2011): SJR 0.564 SNIP 0.914 CiteScore 0.83
ISI indexed (2011): ISI indexed no
Web of Science (2011): Indexed yes
BFI (2010): BFI-level 1
Scopus rating (2010): SJR 0.744 SNIP 0.751
Web of Science (2010): Indexed yes
Scopus rating (2009): SJR 0.455 SNIP 0.454
Web of Science (2009): Indexed yes
Scopus rating (2008): SJR 0.491 SNIP 0.632
Web of Science (2008): Indexed yes
Scopus rating (2007): SJR 0.317 SNIP 0.293
Web of Science (2007): Indexed yes
Web of Science (2006): Indexed yes
Original language: English
Electronic versions:
19.pdf
DOIs:
10.2971/jeos.2009.09003
Links:
http://adsabs.harvard.edu/abs/2009JEOS....4E9003A
Source: orbit
Source-ID: 234839
Publication: Research - peer-review › Journal article – Annual report year: 2009

Simplified 3D isotropic structure for negative index materials in the IR regime

General information
State: Published
Organisations: Plasmonics and Metamaterials, Department of Photonics Engineering
Authors: Andryieuski, A. (Intern), Malureanu, R. (Intern), Lavrinenko, A. (Intern)
The split cube in a cage: bulk negative-index material for infrared applications

We propose the split cube in a cage (SCiC) design for application in producing a bulk metamaterial. Applying realistic material data for thin silver films, we observe an immediate convergence of the effective parameters obtained with a number of layers towards the bulk properties. Results are obtained by two different numerical techniques: the Fourier modal method and the finite integrals method, thus ensuring their validity. The SCiC exhibits a refractive index of $-0.6$ for frequencies close to the telecommunication bands. The fast convergence of effective parameters allows consideration of the SCiC as a bulk (effectively homogeneous) negative-index metamaterial even for a single layer. The bulk-like nature together with the cubic symmetry of the unit cell make the SCiC a promising candidate for potential applications at telecommunication frequencies.
Wave propagation method as an accurate technique for effective refractive index retrieving

An effective parameters retrieval method based on the wave propagation simulation is proposed and compared with the standard S-parameter procedure. The method is free from possible mistakes originated by the multiple branching of solutions in the S-parameter procedure and shows high accuracy. The limitations of the new method are discussed.

General information
State: Published
Organisations: Plasmonics and Metamaterials, Department of Photonics Engineering
Authors: Andryieuski, A. (Intern), Malureanu, R. (Intern), Lavrinenko, A. (Intern)
Pages: 37-39
Publication date: 2009

Host publication information
Title of host publication: Theoretical and Computational Nano-Photonics : AIP Conference Proceedings
Place of publication: Bad Honnef, Germany
Publisher: American Institute of Physics
Main Research Area: Technical/natural sciences
Conference: Theoretical and Computational Nano-Photonics : AIP Conference Proceedings, Bad Honnef, Germany, 01/01/2009
effective parameters, Metamaterials, wave propagation
Source: orbit
Source-ID: 251943
Publication: Research - peer-review › Article in proceedings – Annual report year: 2009

Wave propagation retrieval method for metamaterials: Unambiguous restoration of effective parameters

In this brief report we propose a direct method of effective-parameters restoration that is based on the wave propagation phenomenon. It is easy in implementation, has no unambiguity in retrieving effective properties and is applicable to thick metamaterial (MTM) slabs. The method is validated on the case studies of fishnet, split cube in carcass, and Jerusalem cross MTMs. The constraints of the method are designated.

General information
State: Published
Organisations: Plasmonics and Metamaterials, Department of Photonics Engineering
Authors: Andryieuski, A. (Intern), Malureanu, R. (Intern), Lavrinenko, A. (Intern)
Pages: 193101
Publication date: 2009
Main Research Area: Technical/natural sciences

Publication information
Volume: 80
Issue number: 19
ISSN (Print): 1098-0121
Ratings:
BFI (2017): BFI-level 2
Web of Science (2017): Indexed yes
In this work we will present an accurate description of metallic pads response using RLC theory. In order to calculate such response we take into account several factors including the mutual inductances, precise formula for determining the capacitance and also the pads' resistance considering the variation of permittivity due to small thicknesses. Even if complex, such strategy gives accurate results and we believe that, after more refinement, can be used to completely calculate a complex metallic structure placed on a substrate in a far faster manner than full simulations programs do.

In this paper, a comparison between the placement accuracy of lattice atoms in photonic crystal structures fabricated with different lithographic techniques is made. Using atomic force microscopy measurements and self-developed algorithms for calculating the holes position within less than 0.01nm error, we establish the statistical disorder within such devices.
Photonic wires sidewall roughness measures using AFM capabilities
Within the last years, interest in photonic wires and photonic crystals grew due to their demonstrated ability of controlling light propagation and characteristics. One of the limitations of such devices is due to the induced roughness during the fabrication process. Generally, an increase in roughness leads to loss increase thus limiting the propagation length and postponing the commercialization of such structures. In this paper we present a new algorithm for measuring the sidewall roughness of our devices based on atomic force microscope (AFM) approach. Using this algorithm, the roughness can be quantified and thus actions in decreasing it can be taken improving the device's performance.

General information
State: Published
Organisations: Plasmonics and Metamaterials, Department of Photonics Engineering, Nanophotonic Devices
Authors: Malureanu, R. (Intern), Frandsen, L. H. (Intern)
Publication date: 2008

Host publication information
Title of host publication: SPIE Digital Library
Volume: 6995, No. 1
Place of publication: Strasbourg, France
Main Research Area: Technical/natural sciences
AFM measures, sidewall roughness, photonic wires
Source: orbit
Source-ID: 220029
Publication: Research - peer-review › Article in proceedings – Annual report year: 2008

Fast thermal nanoimprint lithography by a stamp with integrated heater

General information
State: Published
Organisations: Plasmonics and Metamaterials, Department of Photonics Engineering, NSE-Optofluidics Group, NanoSystemsEngineering Section, Department of Micro- and Nanotechnology, Silicon Microtechnology Group, MicroElectroMechnical Systems Section
Authors: Tormen, M. (Ekstern), Malureanu, R. (Intern), Kristensen, A. (Intern), Hansen, O. (Intern)
Pages: 117-118
Publication date: 2007

Host publication information
Title of host publication: MNE 33rd International Conference on Micro- and Nano-Engineering
Main Research Area: Technical/natural sciences
Source: orbit
Source-ID: 205981
Publication: Research - peer-review › Conference abstract in proceedings – Annual report year: 2007

Projects:

Fabrication and characterization of hyperbolic metamaterials
Department of Photonics Engineering
Period: 01/04/2016 – 31/03/2019
Number of participants: 4
Phd Student:
Sukham, Johneph (Intern)
Supervisor:
Lavrinenko, Andrei (Intern)
Stenger, Nicolas (Intern)
Main Supervisor:
Malureanu, Radu (Intern)
Financing sources
Source: Internal funding (public)
**Metal nanocrystal enhanced thin film solar cells**

Department of Photonics Engineering  
Period: 15/01/2011 → 12/12/2014  
Number of participants: 7  
Phd Student: Gritti, Claudia (Intern)  
Supervisor: Kardynal, Beata (Intern)  
Malureanu, Radu (Intern)  
Main Supervisor: Lavrinenko, Andrei (Intern)  
Examiner: Ou, Haiyan (Intern)  
Belov, Pavel (Ekstern)  
Larsen, Arne Nylandsted (Ekstern)

**Financing sources**  
Source: Internal funding (public)

---

**Nanoscale semiconductor optical devices**

Department of Photonics Engineering  
Period: 01/09/2010 → 18/06/2015  
Number of participants: 6  
Phd Student: Kuznetsova, Nadezda (Intern)  
Supervisor: Semenova, Elizaveta (Intern)  
Main Supervisor: Yvind, Kresten (Intern)  
Examiner: Malureanu, Radu (Intern)  
Cirlin, George (Ekstern)  
Kardynal, Beata (Intern)

**Financing sources**  
Source: Internal funding (public)

**Relations**

Publications:

**Optical modulator at THz frequencies**

Department of Photonics Engineering  
Period: 01/05/2010 → 15/01/2014  
Number of participants: 7  
Phd Student: Zalkovskij, Maksim (Intern)  
Supervisor: Jepsen, Peter Uhd (Intern)  
Malureanu, Radu (Intern)
Main Supervisor: Lavrinenko, Andrei (Intern)
Examiner: Mortensen, N. Asger (Intern)
Keiding, Søren Rud (Ekstern)
Planken, P. C. M. (Ekstern)

Financing sources
Source: Internal funding (public)
Name of research programme: Forskningsrådsfinansiering
Project: PhD

THz Control over an Optical Wave
Plasmonics and Metamaterials
Department of Photonics Engineering
Terahertz Technologies and Biophotonics
Belarusian State University
Delft University of Technology
Period: 01/04/2010 → 31/03/2013
Number of participants: 9
Nanotechnology, THz waves, Light control
Acronym: THz COW
Contact person:
Novitsky, Andrey (Ekstern)
Planken, Paul C.M. (Ekstern)
Project participant:
Malureanu, Radu (Intern)
Boltasseva, Alexandra (Intern)
Cooke, David (Intern)
Ivinskaya, Aliaksandra (Intern)
Novitsky, Andrey (Intern)
Jepsen, Peter Uhd (Intern)
Project Manager, organisational:
Lavrinenko, Andrei (Intern)

Financing sources
Source: Forskningsrådene - Andre
Name of research programme: Forskningsrådene - Andre
Amount: 5,756,400.00 Danish Kroner
Project

Negative Index Materials and Plasmonic Antennas Based Nanocoupler
Department of Photonics Engineering
Period: 01/06/2008 → 23/11/2011
Number of participants: 6
Phd Student:
Andryieuski, Andrei (Intern)
Supervisor:
Malureanu, Radu (Intern)
Main Supervisor:
Lavrinenko, Andrei (Intern)
Examiner:
Breinbjerg, Olav (Intern)
Martin, Olivier J.F. (Ekstern)
Willatzen, Morten (Intern)
Financing sources
Source: Internal funding (public)
Name of research programme: Forskningsrådsfinansiering
Project: PhD

Negative Index Materials Based nano-Couplers
Department of Photonics Engineering
Period: 01/06/2008 → 31/12/2011
Number of participants: 3
Acronym: NIMbus
Project ID: 70421
Project participant:
Malureanu, Radu (Intern)
Andryieuski, Andrei (Intern)

Project Manager, organisational:
Lavrinenko, Andrei (Intern)

Financing sources
Source: Unknown
Name of research programme: Ukendt
Project

Activities:

Third International Workshop on Theoretical and Computational Nanophotonics (TaCoNa-Photonics 2010)
Period: 3 Nov 2010 → 5 Nov 2010
Radu Malureanu (Speaker)
Department of Photonics Engineering
Plasmonics and Metamaterials

Description
Homogenization of metamaterials is very important as it makes possible description in terms of effective parameters. In this contribution we consider the homogenization of chiral metamaterials. We show that for some metamaterials there is an optimal meta-atom size which depends on the coupling between meta-atoms. We introduce numerical criterion of homogeneity on the basis of the Bloch modes dispersion diagram calculation and a tool to predict the homogeneity limit. We show that some metamaterials with strong coupling between meta-atoms cannot be considered as homogeneous at all.
Place: Bad Honnef, Germany
Degree of recognition: International

Related event
3rd International Workshop on Theoretical and Computational Nano-Photonics
03/11/2010 → 05/11/2010
Bad Honnef, Germany
Activity: Talks and presentations › Conference presentations

4th International Congress on Advanced Electromagnetic Materials in Microwaves and Optics
Period: 13 Sep 2010 → 16 Sep 2010
Radu Malureanu (Participant)
Department of Photonics Engineering
Plasmonics and Metamaterials

Description
Metamaterial imaging applications require optical isotropy. We show that highly symmetric unit cells do not necessarily exhibit this property. We prove that the dispersion relation can be tailored using a supercell metamaterial. Such metamaterial exhibits an isotropic negative index close to -1. Its potential for image formation is discussed.

Related event
In this presentation we extend the wave propagation method for the retrieval of the effective properties to the case of chiral metamaterials with circularly polarised eigenwaves. The method is unambiguous, simple and provides bulk effective parameters. Advantages and constraints are discussed.

**Related event**

*International Congress on Advanced Electromagnetic Materials in Microwaves and Optics*
Period: 13 Sep 2010
Radu Malureanu (Participant)

Department of Photonics Engineering
Plasmonics and Metamaterials

**Description**
In this presentation we extend the wave propagation method for the retrieval of the effective properties to the case of chiral metamaterials with circularly polarised eigenwaves. The method is unambiguous, simple and provides bulk effective parameters. Advantages and constraints are discussed.

**Related external organisation**

Unknown external organisation
Activity: Talks and presentations › Conference presentations

**International Workshop on Photonic Nanomaterials (PhoNa-2010); 6 (Event)**
Period: 24 Mar 2010 → 25 Mar 2010
Radu Malureanu (Reviewer)

Department of Photonics Engineering
Plasmonics and Metamaterials

**Description**
In this work we present an extension of the wave propagation retrieval method to the case of chiral metamaterials that possess circularly polarized eigenwaves.
Related event
International Workshop on Photonic Nanomaterials (PhoNa-2010); 6: Wave propagation method as a characterization tool for chiral metamaterials
24/03/2010 → 25/03/2010
Jena, Germany
Activity: Research › Peer review of manuscripts

Dansk Fysisk Selskab Årsmøde 2009
Radu Malureanu (Participant)
Department of Photonics Engineering
Plasmonics and Metamaterials

Description
Bulk isotropic negative-index metamaterial for infrared: Session 2, Nanophysics and nanomaterials

Negative-index metamaterials (NIMs) are artificially structured materials exhibiting both negative electric permittivity and magnetic permeability over some frequency range. They propose great opportunities to control the light and to create such devices as invisibility cloaks, superresolution lenses, nanocouplers etc. Nowadays there is a lack of the isotropic negative-index material designs for infrared and optical wavelengths. We present the nested structures approach to design isotropic NIM in which the negative permeability part is embedded into the negative permittivity part. We also present a design of NIM working at telecommunication wavelengths and showing $n = -1$ and figure of merit higher than 2. The effective properties are obtained from numerical simulations for 1-5 layers of metamaterial and show fine convergence with the number of layers. We describe the physical behaviour of NIM and its constituent parts and prove its isotropy. The time-domain simulations of the wave propagation through 20 NIM layers prove its negative refractive index behaviour. The designed structure is a promising building block for construction of an isotropic negative-index material. The proposed nested structures approach is useful for designing isotropic metamaterials.

Place: Copenhagen, Denmark
Degree of recognition: National

Related event
Dansk Fysisk Selskab Årsmøde 2009
16/06/2009 → 18/06/2009
Copenhagen, Denmark
Activity: Attending an event › Participating in or organising workshops, courses, seminars etc.

3D isotropic double negative material design for infrared
Period: 3 Dec 2008 → 5 Dec 2008
Radu Malureanu (Participant)
Department of Photonics Engineering
Plasmonics and Metamaterials

Description
Conference name: The First International Workshop on Theoretical and COmputational NanoPhotonics TaCoNa-Photonics 2008
We propose a new metamaterial unit cell design "cube-in-cage" with a unit cell cubic symmetry, providing negative refractive index $n=-2.4$, figure-of-merit 2.4 and relatively high transmission 16% for infrared telecommunication wavelengths near 1.55 mkm.

Related event
3D isotropic double negative material design for infrared
03/12/2008 → 05/12/2008
Bad Honnef, Germany
Activity: Attending an event › Participating in or organising workshops, courses, seminars etc.

Press clippings:
Usynlighedskappe i mikroformat skjuler guldbule
Radu Malureanu
12/03/2010
Department of Photonics Engineering, Plasmonics and Metamaterials

Media contribution (1)

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Press / Media