Mode conversion enables optical pulling force in photonic crystal waveguides

We propose a robust scheme to achieve optical pulling force using the guiding modes supported in a hollow core double-mode photonic crystal waveguide instead of the structured optical beams in free space investigated earlier. The waveguide under consideration supports both the 0th order mode with a larger forward momentum and the 1st order mode with a smaller forward momentum. When the 1st order mode is launched, the scattering by the object inside the waveguide results in the conversion from the 1st order mode to the 0th order mode, thus creating the optical pulling force according to the conservation of linear momentum. We present the quantitative agreement between the results derived from the mode conversion analysis and those from rigorous simulation using the finite-difference in the time-domain numerical method. Importantly, the optical pulling scheme presented here is robust and broadband with naturally occurred lateral equilibriums and has a long manipulation range. Flexibilities of the current configuration make it valuable for the optical force tailoring and optical manipulation operation, especially in microfluidic channel systems.
Analytical solutions for waves in spherically- and cylindrically-symmetric inhomogeneous media

We present the operator approach of finding material parameters of inhomogeneous bianisotropic media, the Maxwell equations in which have closed-form solutions. It is applicable to spherically- and cylindrically-symmetric media. Scattering theory for the inhomogeneous objects in question is developed.

General information
State: Published
Organisations: Department of Photonics Engineering, Plasmonics and Metamaterials, ITMO University
Authors: Novitsky, A. (Intern), Shalin, A. S. (Ekstern), Lavrinenko, A. (Intern)
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Comparison of Five Computational Methods for Computing Q Factors in Photonic Crystal Membrane Cavities

Five state-of-the-art computational methods are benchmarked by computing quality factors and resonance wavelengths in photonic crystal membrane L5 and L9 line defect cavities. The convergence of the methods with respect to resolution, degrees of freedom and number of modes is investigated. Special attention is paid to the influence of the size of the computational domain. Convergence is not obtained for some of the methods, indicating that some are more suitable than others for analysing line defect cavities.

Magnetic field concentration with coaxial silicon nanocylinders in the optical spectral range

Possibility of magnetic energy accumulation inside silicon nanoparticles at the conditions of resonant optical responses is investigated theoretically. Thermagnetic field distributions inside silicon nanocylinders with and without coaxial through holes are calculated using full-wave numerical approach. It is demonstrated that such systems can be used for control and manipulation of optical magnetic fields providing their enhancement up to 26 times at the condition of optical resonances. Obtained results can be used for realization of nanoantennas and nanolasers, in which magnetic optical transitions play significant roles.

Magnetic field concentration with coaxial silicon nanocylinders in the optical spectral range

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Matter-Wave Tractor Beams

Optical and acoustic tractor beams are currently the focus of intense research due to their counterintuitive property of exerting a pulling force on small scattering objects. In this Letter we propose a matter-wave tractor beam and utilize the de
Broglie waves of nonrelativistic matter particles in analogy to “classical” tractor beams. We reveal the presence of the quantum-mechanical pulling force for the variety of quantum mechanical potentials observing the resonant enhancement of the pulling effect under the conditions of the suppressed scattering known as the Ramsauer-Townsend effect. We also derive the sufficient conditions on the scattering potential for the emergence of the pulling force and show that, in particular, a Coulomb scatterer is always shoved, while a Yukawa (screened Coulomb) scatterer can be drawn. Pulling forces in optics, acoustics, quantum mechanics, and classical mechanics are compared, and the matter-wave pulling force is found to have exclusive properties of dragging slow particles in short-range potentials. We envisage that the use of tractor beams could lead to the unprecedented precision in manipulation with atomic-scale quantum objects.
Non-Diffractive Tractor Beams

Pulling optical force discovered recently in the theory and experiment has drawn great attention owing to its counterintuitive nature and promising applications. Pulling force originates from the enhanced forward light scattering that in accordance with the momentum conservation conveys light momentum to particles in the backward direction. The amplified forward scattering is achieved through the interaction of multipoles, conventionally electric and magnetic dipole moments. In this talk we give an overview of the tractor beams in optics, acoustics, classical and quantum mechanics. We demonstrate how to ease the conditions required in experiment for realization of the optical tractor beams using the cylindrical objects. We pay a particular attention to the case of the pulling optical force due to the interaction of magnetic dipole and quadrupole moments.

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Organisations: Department of Photonics Engineering, Plasmonics and Metamaterials, Soochow University, Belarusian State University, National University of Singapore
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Electromagnetic beams, Pulling forces, Micromanipulation
Publication: Research - peer-review › Article in proceedings – Annual report year: 2017

Pulling cylindrical particles using a soft-nonparaxial tractor beam
In order to pull objects towards the light source a single tractor beam inevitably needs to be strongly nonparaxial. This stringent requirement makes such a tractor beam somewhat hypothetical. Here we reveal that the cylindrical shape of dielectric objects can effectively mitigate the nonparaxiality requirements, reducing the incidence angle of the partial plane waves of the light beam down to 45 degrees and even to 30 degrees for respectively dipole and dipole-quadrupole objects. The optical pulling force attributed to the interaction of magnetic dipole and magnetic quadrupole moments of dielectric cylinders occurs due to the TE rather than TM polarization. Therefore, the polarization state of the incident beam
can be utilized as an external control for switching between the pushing and pulling forces. The results have application values towards optical micromanipulation, transportation and sorting of targeted particles.

General information
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Organisations: Department of Photonics Engineering, Plasmonics and Metamaterials, Harbin Institute of Technology, National University of Singapore, Soochow University
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Spherically symmetric inhomogeneous bianisotropic media: Wave propagation and light scattering
We develop a technique for finding closed-form expressions for electromagnetic fields in radially inhomogeneous bianisotropic media, both the solutions of the Maxwell equations and material tensors being defined by the set of auxiliary two-dimensional matrices. The approach is applied to determine the scattering cross-sections by spherical particles, the fields inside which correspond to the Airy-exponential waves.

General information
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Organisations: Department of Photonics Engineering, Plasmonics and Metamaterials, ITMO University
Authors: Novitsky, A. (Intern), Shalin, A. S. (Ekstern), Lavrinenko, A. (Intern)
Number of pages: 11
We numerically demonstrate that a pronounced dipole-quadrupole (DQ) Fano resonance (FR) induced lateral force can be exerted on a dielectric particle 80 nm in radius (R-sphere = 80 nm) that is placed 5 nm above an asymmetric bow-tie nanoantenna array based on Au/Ge2Sb2Te5 dual layers. The DQ-FR-induced lateral force achieves a broad tuning range in the mid-infrared region by changing the states of the Ge2Sb2Te5 dielectric layer between amorphous and crystalline and in turn pushes the nanoparticle sideways in the opposite direction for a given wavelength. The mechanism of lateral force reversal is revealed through optical singularity in the Poynting vector. A thermal-electric simulation is adopted to investigate the temporal change of the Ge2Sb2Te5 film's temperature, which demonstrates the possibility of transiting the Ge2Sb2Te5 state by electrical heating. Our mechanism by tailoring the DQ-FR-induced lateral force presents clear advantages over the conventional nanoparticle manipulation techniques: it possesses a pronounced sideways force under a low incident light intensity of 10 mW/μm², a fast switching time of 2.6 μs, and a large tunable wavelength range. It results in a better freedom in flexible nanomechanical control and may provide a new means of biomedical sensing and nano-optical conveyor belts.
Operator approach to effective medium theory to overcome a breakdown of Maxwell Garnett approximation

We elaborate on an operator approach to effective medium theory for homogenization of the periodic multilayered structures composed of nonmagnetic isotropic materials, which is based on equating the spatial evolution operators for the original structure and its effective alternative. We show that the zeroth-, first-, and second-order approximations of the operator effective medium theory correspond to electric dipoles, chirality, and magnetic dipoles plus electric quadrupoles, respectively. We discover that the spatially dispersive bianisotropic effective medium obtained in the second-order approximation perfectly replaces a multilayered composite and does not suffer from the effective medium approximation breakdown that happened near the critical angle of total internal reflection found previously in the conventional effective medium theory. We establish the criterion of the validity of the conventional effective medium theory depending on the ratio of unit-cell length to the wavelength, the number of unit cells, and the angle of incidence. The operator approach to effective medium theory is applicable for periodic and nonperiodic layered systems, being a fruitful tool in the fields of metamaterials and subwavelength nanophotonics.
Photon absorption and photocurrent in solar cells below semiconductor bandgap due to electron photoemission from plasmonic nanoantennas

We model the electron photoemission from metal nanoparticles into a semiconductor in a Schottky diode with a conductive oxide electrode hosting the nanoparticles. We show that plasmonic effects in the nanoparticles lead to a substantial enhancement in photoemission compared with devices with continuous metal films. Optimally designed metal nanoparticles can provide an effective mechanism for the photon absorption in the infrared range below the semiconductor bandgap, resulting in the generation of a photocurrent in addition to the photocurrent from band-to-band absorption in a semiconductor. Such structure can form the dais of the development of plasmonic photoemission enhanced solar cells.
Scattering of Light and Pulling Optical Forces for Hyperbolic-Metamaterial Spheres
We discuss electromagnetic fields and optical forces acting on microspheres made of extremely anisotropic medium. We propose an energy-based criterion for choosing an appropriate solution of Maxwell's equations inside the sphere when two solutions are singular at the center. We investigate the material parameters of a lossy hyperbolic-metamaterial sphere that can be pulled by a nonparaxial, gradientless Bessel beam.

Coherence matrix of plasmonic beams
We consider monochromatic electromagnetic beams of surface plasmon-polaritons created at interfaces between dielectric media and metals. We theoretically study non-coherent superpositions of elementary surface waves and discuss their spectral degree of polarization, Stokes parameters, and the form of the spectral coherence matrix. We compare the polarization properties of the surface plasmon-polaritons as three-dimensional and two-dimensional fields concluding that the latter is superior.
Metamaterial characterization using Boltzmann's kinetic equation for electrons

Statistical properties of electrons in metals are taken into consideration to describe the microscopic motion of electrons. Assuming degenerate electron gas in metal, we introduce the Boltzmann kinetic equation to supplement Maxwell's equations. The solution of these equations clearly shows the resonant behavior of electronic response to an external electromagnetic field. We demonstrate the approach for planar and circular geometries of the metamolecules.

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.
New Nanoplasmonic Photovoltaics Based on Enhanced Photoemission from Plasmonic Nanoantennas

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*Publication:* Research - peer-review › Article in proceedings – Annual report year: 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.

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*Organisations:* Department of Photonics Engineering, Plasmonics and Metamaterials, Terahertz Technologies and Biophotonics, University of Wuppertal, Institute for Product Development
*Authors:* Zalkovskij, M. (Intern), Malureanu, R. (Intern), Kremers, C. (Ekstern), Chigrin, D. N. (Ekstern), Novitsky, A. (Intern), Zhukovsky, S. (Intern), Tang, P. T. (Ekstern), Jepsen, P. U. (Intern), Lavrinenko, A. (Intern)
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- Scopus rating (2014): SJR 5.019 SNIP 4.568 CiteScore 8.62
- Web of Science (2014): Indexed yes
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- Scopus rating (2013): SJR 5.155 SNIP 4.864 CiteScore 9.26
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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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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
State: Published
Organisations: Department of Photonics Engineering, Plasmonics and Metamaterials, Terahertz Technologies and Biophotonics, Institute for Product Development, University of Wuppertal
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Title of host publication: 2013 15th International Conference on Transparent Optical Networks (ICTON)
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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.

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.
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.

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Organisations: Department of Photonics Engineering, Plasmonics and Metamaterials, Terahertz Technologies and Biophotonics, University of Wuppertal
Authors: Zalkovskij, M. (Intern), Malureanu, R. (Intern), Novitsky, A. (Intern), Jepsen, P. U. (Intern), Lavrinenko, A. (Intern), Kremers, C. (Ekstern), Chigrin, D. N. (Ekstern)
Asymmetric transmission in planar chiral split-ring metamaterials: Microscopic Lorentz-theory approach

The electronic Lorentz theory is employed to explain the optical properties of planar split-ring metamaterials. Starting from the dynamics of individual free carriers, the electromagnetic response of an individual split-ring meta-atom is determined, and the effective permittivity tensor of the metamaterial is calculated for normal incidence of light. Whenever the split ring lacks in-plane mirror symmetry, the corresponding permittivity tensor has a crystallographic structure of an elliptically dichroic medium, and the metamaterial exhibits optical properties of planar chiral structures. Its transmission spectra are different for right-handed versus left-handed circular polarization of the incident wave, so the structure changes its transmittance when the direction of incidence is reversed. The magnitude of this change is shown to be related to the geometric parameters of the split ring. The proposed approach can be generalized to a wide variety of metal-dielectric metamaterial geometries.
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.

General information
State: Published
Organisations: Department of Photonics Engineering, Plasmonics and Metamaterials, Nanophotonics Theory and Signal Processing, Technical University of Denmark, Politehnica University
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Number of pages: 2
Publication date: 2012
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.

Field approach in the transformation optics concept

An alternative, field-based formulation of transformation optics is proposed. Field transformations are expressed in the language of boundary conditions for the electromagnetic fields facilitated through the introduction of generalized potential functions. It is shown that the field-based approach is equivalent to the conventional coordinate-transformation approach but is preferable when looking for specific field distribution. A set of example devices such as invisibility cloaks, concentrators, rotators, and transformation optics lenses capable of creating light beams with predetermined field distribution (e.g., Gaussian and sinusoidal) is studied to validate the effectiveness of the field-based formulation. As for the boundary conditions for the cloaked region the absence of the normal component of the Poynting vector is justified. In the frames of the field-based approach the physical reasons behind infinite components (singularities) of the material parameters of transformation optics devices are straightforwardly revealed.
Graphene hyperlens for terahertz radiation

We propose the structured graphene terahertz hyperlens that allows overcoming natural diffraction limit and resolving subwavelength features. The proposed hyperlens can have applications in terahertz spectroscopy and imaging.

General information

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Organisations: Department of Photonics Engineering, Plasmonics and Metamaterials, University of Wuppertal
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Publication: Research - peer-review › Article in proceedings – Annual report year: 2012

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.
Material-Independent and Size-Independent Tractor Beams for Dipole Objects

A Bessel beam without an axial gradient can exert a pulling force on an object [A. Novitsky, C. W. Qiu, and H. Wang, Phys. Rev. Lett. 107 203601 (2011)]. However, it cannot be called a “tractor beam” per se, as long as the light pulling effect is ultrasensitive to the object’s material and size, a perturbation of which will make the optical traction go away. In this Letter, we investigate and report on the universality for a Bessel beam to be either a material-independent or size-independent optical tractor beam within the dipolar regime. Moreover, a general condition for a nonparaxial laser to be simultaneously a material- and size-independent tractor beam is proposed. These universal pulling effects and conditions are discussed in association with insight on modified far-field scattering, scattering resonances, and induced polarizabilities. Interestingly, we find that the acoustic pulling force exhibits only size independence, owing to the acoustic scattering theory in contrast to the light scattering counterpart. The findings pave the way for the realistic engineering and application of universal tractor beams pulling a wide variety of objects.
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.

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Organisations: Department of Photonics Engineering, Plasmonics and Metamaterials, Terahertz 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.

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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 $P \ll \lambda$. 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.
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 10 kV/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.

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 10 kV/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
State: Published
Organisations: Department of Photonics Engineering, Plasmonics and Metamaterials, Terahertz Technologies and Biophotonics
Authors: Novitsky, A. (Intern), Zalkovskij, M. (Intern), Malureanu, R. (Intern), Jepsen, P. U. (Intern), Lavrinenko, A. (Intern)
Pages: 3903-3905
Publication date: 2012
Main Research Area: Technical/natural sciences

Publication information
Journal: Optics Letters
Volume: 37
Issue number: 18
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Ratings: BFI (2017): BFI-level 2
BFI (2016): BFI-level 2
Scopus rating (2016): CiteScore 3.54 SJR 1.864 SNIP 1.658
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 2
Scopus rating (2015): SJR 2.142 SNIP 1.642 CiteScore 3.53
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 2
Scopus rating (2014): SJR 2.497 SNIP 2.056 CiteScore 3.86
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 2
Scopus rating (2013): SJR 2.458 SNIP 2.095 CiteScore 3.95
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
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, Terahertz Technologies and Biophotonics, Bergische Universität Wuppertal, Fudan University
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 As$_2$S$_3$ 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 As$_2$S$_3$ compound at higher frequencies. In addition, As$_2$S$_3$ displays two transparency regions, at 7-8 THz and 12.2 THz, of potential interest for future nonlinear applications in the THz range.
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.

General information
State: Published
Organisations: Department of Photonics Engineering, Plasmonics and Metamaterials, Terahertz Technologies and Biophotonics, National Institute for Optoelectronics
Authors: Zalkovskij, M. (Intern), Malureanu, R. (Intern), Novitsky, A. (Intern), Savastru, D. (Ekstern), Popescu, A. (Ekstern), Lavrinenko, A. (Intern), Jepsen, P. U. (Intern)
Number of pages: 2
Pages: CM1L.2
Publication date: 2012
Asymmetric transmission in planar chiral metamaterials: microscopic explanation

Lorentz electron theory is a powerful approach for description of macroscopic parameters of a medium based on microscopic characteristics of the individual electron. For a planar array of chiral metallic split rings, we determine the averaged electron's characteristics in a split ring and apply them to derive the permittivity tensor of the homogenized medium. The effective material parameters obtained describe anisotropic dichroic material, where electromagnetic waves are governed by enantiomeric and directional asymmetry – the signature property of planar chiral metamaterials.

Field-based transformation optics

Instead of common definition of the transformation-optics devices via the coordinate transformation we offer the approach founded on boundary conditions for the fields. We demonstrate the effectiveness of the approach by two examples: two-shell cloak and concentrator of electric field. We believe that the field-based approach is quite important for effective field control.
Ideal conversion of surface waves: ИДЕАЛЬНАЯ КОНВЕРСИЯ ПОВЕРХНОСТНЫХ ВОЛН

General information
State: Published
Organisations: Plasmonics and Metamaterials, Department of Photonics Engineering, Belarusian State University
Authors: Novitsky, A. (Intern), Galynsky, V. M. (Ekstern)
Pages: 646-647
Publication date: 2011

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Title of host publication: Proceedings of Optics-2011
Main Research Area: Technical/natural sciences
Electronic versions:
prod11319450097784.optics2011conversionSW.pdf
Links:
Source: orbit
Source-ID: 286155
Publication: Research - peer-review › Article in proceedings – Annual report year: 2011

Increased electron photoemission from plasmonic nanoparticles and photoemission enhanced solar cells
Numerical simulation shows possibility to enhance substantially (by one-two orders) the electron photoemission through surface of metal nanoparticles embedded into photovoltaic structures. This, in turn, can lead to increase of the solar cells efficiency due to efficient light-to-electricity transformation below the solar cell semiconductor bandgap.

General information
State: Published
Organisations: Plasmonics and Metamaterials, Department of Photonics Engineering, Light Energy Harvesting, P. N. Lebedev Physical Institute
Authors: Novitsky, A. (Intern), Uskov, A. (Intern), Gritti, C. (Intern), Protsenko, I. E. (Ekstern), Kardynal, B. (Intern), Lavrinenko, A. (Intern)
Publication date: 2011

Host publication information
Title of host publication: Proceedings of the Asia-Pacific Conference on Fundamental Problems of Opto-and Microelectronics
Main Research Area: Technical/natural sciences
Conference: Asia-Pacific Conference on Fundamental Problems of Opto-and Microelectronics, Moscow-Samara, Russia, 01/01/2011
Links:
http://apcom2011.org/
Source: orbit
Source-ID: 284915
Publication: Research - peer-review › Article in proceedings – Annual report year: 2011

Inverse problem in transformation optics
The straightforward method of transformation optics implies that one starts from the coordinate transformation and determines the Jacobian matrix, the fields and material parameters of the cloak. However, the coordinate transformation appears as an optional function: it is not necessary to know it. We offer the solution of some sort of inverse problem: starting from the fields in the invisibility cloak we directly derive the permittivity and permeability tensors of the cloaking shell. This approach can be useful for finding material parameters for the specified electromagnetic fields in the cloaking shell without knowing the coordinate transformation.

General information
State: Published
Organisations: Plasmonics and Metamaterials, Department of Photonics Engineering
Invisibility devices with realistic material parameters: УСТРОЙСТВА НЕВИДИМОСТИ С УЧЕТОМ РЕАЛЬНЫХ МАТЕРИАЛЬНЫХ ПАРАМЕТРОВ СРЕД

General information
**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.

**General information**

State: Published
Organisations: Plasmonics and Metamaterials, Department of Photonics Engineering
Authors: Novitsky, A. (Intern), Zalkovskij, M. (Intern), Malureanu, R. (Intern), Lavrinenko, A. (Intern)
Pages: 5495
Publication date: 2011
Main Research Area: Technical/natural sciences

**Publication information**

Journal: Optics Communications
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Ratings:
- BFI (2017): BFI-level 2
- Web of Science (2017): Indexed yes
- BFI (2016): BFI-level 2
- Scopus rating (2016): SJR 0.633 SNIP 0.924 CiteScore 1.65
- Web of Science (2016): Indexed yes
- BFI (2015): BFI-level 2
- Scopus rating (2015): SJR 0.711 SNIP 0.987 CiteScore 1.62
- Web of Science (2015): Indexed yes
- BFI (2014): BFI-level 2
- Scopus rating (2014): SJR 0.719 SNIP 1.058 CiteScore 1.62
- Web of Science (2014): Indexed yes
- BFI (2013): BFI-level 2
- Scopus rating (2013): SJR 0.746 SNIP 1.175 CiteScore 1.78
- ISI indexed (2013): ISI indexed yes
- Web of Science (2013): Indexed yes
- BFI (2012): BFI-level 2
- Scopus rating (2012): SJR 0.813 SNIP 1.151 CiteScore 1.63
- ISI indexed (2012): ISI indexed yes
New Circular Fractal Sensors for Near-infrared Wavelengths

General information
State: Published
Organisations: Plasmonics and Metamaterials, Department of Photonics Engineering, Politehnica University
Authors: Malureanu, R. (Intern), Sandru, A. (Ekstern), Novitsky, A. (Intern), Lavrinenko, A. (Intern)
Number of pages: 585
Publication date: 2011

Host publication information
Title of host publication: PIERS 2011 Suzhou : Progress In Electromagnetics Research Symposium
Series: Progress in Electromagnetics Research Symposium
ISSN: 1559-9450
Main Research Area: Technical/natural sciences
Non-paraxial beam to push and pull microparticles

We discuss a feasibility of the pulling (backward) force acting on a spherical microparticle in a non-paraxial Bessel beam. The effect can be explained by the strong interaction of particle's multipoles or by the conservation of momentum in the system "photons-particle." It is remarkable that the pulling force revealed does not require the beam focusing or high-index ambient medium. The necessary condition of arising of the backward force is the strong non-paraxiality of an electromagnetic beam. We expect this phenomenon will open new horizons in optical micromanipulation.

General information
State: Published
Organisations: Plasmonics and Metamaterials, Department of Photonics Engineering, National University of Singapore
Authors: Novitsky, A. (Intern), Qiu, C. (Ekstern)
Pages: 162-164
Publication date: 2011

Host publication information
Title of host publication: AIP Conference Proceedings : The Fourth International Workshop on Theoretical and Computational Nanophotonics
Publisher: American Institute of Physics
Volume: 1398

Series: Uden navn
ISSN: 0094-243X
Main Research Area: Technical/natural sciences
Conference: 4th International Workshop on Theoretical and Computational Nanophotonics, Bad Honnef, Germany, 26/10/2011 - 26/10/2011
DOI: 10.1063/1.3644245

Single Gradientless Light Beam Drags Particles as Tractor Beams

Usually a light beam pushes a particle when the photons act upon it. We investigate the optical forces by nonparaxial gradientless beams and find that the forces can drag suitable particles all the way towards the light source. The major criterion of realizing the backward dragging force is the strong nonparaxiality of the light beam, which contributes to the pulling force owing to momentum conservation. The nonparaxiality of the Bessel beam can be manipulated to possess a dragging force along both the radial longitudinal directions, i.e., a "tractor beam" with stable trajectories is achieved. © 2011 American Physical Society.

General information
State: Published
Organisations: Plasmonics and Metamaterials, Department of Photonics Engineering, National University of Singapore, Agency for Science, Technology and Research
Authors: Novitsky, A. (Intern), Qiu, C. (Ekstern), Wang, H. (Ekstern)
Pages: 203601
Publication date: 2011
Main Research Area: Technical/natural sciences

Publication information
Journal: Physical Review Letters
Volume: 107
Issue number: 20
ISSN (Print): 0031-9007
Ratings:
BFI (2017): BFI-level 2
Web of Science (2017): Indexed yes
BFI (2016): BFI-level 2
Scopus rating (2016): CiteScore 6.33 SJR 3.56 SNIP 2.133
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 2
Scopus rating (2015): SJR 3.823 SNIP 2.205 CiteScore 5.76
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 2
Scopus rating (2014): SJR 5.027 SNIP 2.646 CiteScore 6.62
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 2
Scopus rating (2013): SJR 5.674 SNIP 2.796 CiteScore 7.46
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 2
Scopus rating (2012): SJR 6.243 SNIP 2.845 CiteScore 7.19
ISI indexed (2012): ISI indexed yes
Web of Science (2012): Indexed yes
BFI (2011): BFI-level 2
Scopus rating (2011): SJR 6.252 SNIP 2.886 CiteScore 7.02
ISI indexed (2011): ISI indexed yes
Web of Science (2011): Indexed yes
BFI (2010): BFI-level 2
Scopus rating (2010): SJR 6.418 SNIP 2.764
Web of Science (2010): Indexed yes
BFI (2009): BFI-level 2
Scopus rating (2009): SJR 6.342 SNIP 2.94
Web of Science (2009): Indexed yes
BFI (2008): BFI-level 2
Scopus rating (2008): SJR 6.223 SNIP 2.854
Web of Science (2008): Indexed yes
Scopus rating (2007): SJR 6.14 SNIP 2.862
Web of Science (2007): Indexed yes
Scopus rating (2006): SJR 5.645 SNIP 2.807
Web of Science (2006): Indexed yes
Scopus rating (2005): SJR 5.35 SNIP 2.938
Web of Science (2005): Indexed yes
Scopus rating (2004): SJR 5.312 SNIP 2.976
Web of Science (2004): Indexed yes
Scopus rating (2003): SJR 5.33 SNIP 2.93
Web of Science (2003): Indexed yes
Scopus rating (2002): SJR 5.441 SNIP 3.089
Web of Science (2002): Indexed yes
Web of Science (2001): Indexed yes
Scopus rating (2000): SJR 5.92 SNIP 3.111
Web of Science (2000): Indexed yes
Scopus rating (1999): SJR 6.185 SNIP 2.979
Original language: English
Electronic versions:
63E0Ad01.pdf
Wavelength-independent field enhancement in subwavelength gratings

We show that lamellar metal gratings exhibit total transmission of incident radiation and strong nonresonant electric field enhancement in extremely subwavelength regime (in the nanometer-sized slits). With high accuracy the enhancement equals the ratio of the grating period to the slit width, it is independent on the wavelength and metal thickness.

General information
State: Published
Organisations: Department of Photonics Engineering, Plasmonics and Metamaterials, Max Planck Institute
Authors: Ivinskaya, A. (Intern), Novitsky, A. (Intern), Shyroki, D. (Ekstern), Zalkovskij, M. (Intern), Malureanu, R. (Intern), Lavrinenko, A. (Intern)
Pages: 513-515
Publication date: 2011

Conversion from surface wave to surface wave on reflection

We discuss the reflection and transmission of an incident surface wave to a pure surface wave state at another interface. This is allowed only for special media parameters: at least one of the media must be magnetic. We found such material characteristics that the obliquely incident surface wave can be transmitted without changing its direction (nevertheless the amplitude varies). For other media parameters, only normally incident surface waves can be converted to surface waves. We propose applications of the predicted conversion as a beam splitter and polarization filter for surface waves.

General information
State: Published
Organisations: Plasmonics and Metamaterials, Department of Photonics Engineering
Authors: Novitsky, A. (Intern)
Pages: 115705
Publication date: 2010
Main Research Area: Technical/natural sciences

Publication information
Volume: 12
Issue number: 11
ISSN (Print): 1464-4258
Ratings:
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Web of Science (2017): Indexed Yes
Scopus rating (2016): CiteScore 1.63
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 1
Scopus rating (2015): CiteScore 1.44
Web of Science (2015): Indexed yes
Fast closed-form calculation of THz field enhancement in a metal nanoslit

**General information**
State: Published
Organisations: Plasmonics and Metamaterials, Department of Photonics Engineering
Authors: Novitsky, A. (Intern), Lavrinenko, A. (Intern)
Publication date: 2010
Event: Poster session presented at 3rd International Workshop on Theoretical and Computational Nano-Photonics, Bad Honnef, Germany.
Main Research Area: Technical/natural sciences
Source: orbit
Source-ID: 268643
Publication: Research - peer-review › Poster – Annual report year: 2010

THz field enhancement by a metal nanoslit: a simple model
The near-field enhancement in the sub-skin-depth regime fundamentally differs from the extraordinary optical transmission. We propose a simple model for explanation of the THz field enhancement in the metal slit in the sub-skin-depth regime. In our opinion the enhanced field is generated by the charges at the edges of the slit and therefore can be easily estimated. Conclusions of the model provide nice coincidence with the published experimental data.

**General information**
State: Published
Organisations: Plasmonics and Metamaterials, Department of Photonics Engineering
Transformation-based spherical cloaks designed by an implicit transformation-independent method: theory and optimization

Based on the concept of the cloak generating function, we propose an implicit transformation-independent method for the required parameters of spherical cloaks without knowing the needed coordinate transformation beforehand. A non-ideal discrete model is used to calculate and optimize the total scattering cross-sections of different profiles of the generating function. A bell-shaped quadratic spherical cloak is found to be the best candidate, which is further optimized by controlling the design parameters involved. Such improved invisibility is steady even when the model is highly discretized.

General information
State: Published
Organisations: Massachusetts Institute of Technology, Laboratoire de Génie Electrique de Paris, Belarusian State University
Authors: Novitsky, A. (Intern), Qiu, C. (Ekstern), Zouhdi, S. (Ekstern)
Pages: 113001
Publication date: 2009
Main Research Area: Technical/natural sciences

Publication information
Journal: New Journal of Physics
Volume: 11
ISSN (Print): 1367-2630
Ratings:
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Web of Science (2017): Indexed Yes
BFI (2016): BFI-level 2
Scopus rating (2016): CiteScore 2.97 SJR 1.788 SNIP 1.031
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 2
Scopus rating (2015): SJR 1.938 SNIP 1.047 CiteScore 2.8
Web of Science (2015): Indexed yes
BFI (2014): BFI-level 2
Scopus rating (2014): SJR 2.806 SNIP 1.307 CiteScore 2.89
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 2
Scopus rating (2013): SJR 2.871 SNIP 1.372 CiteScore 2.77
ISI indexed (2013): ISI indexed yes
Web of Science (2013): Indexed yes
BFI (2012): BFI-level 2
Scopus rating (2012): SJR 3.352 SNIP 1.533 CiteScore 3.4
ISI indexed (2012): ISI indexed yes
Web of Science (2012): Indexed yes
BFI (2011): BFI-level 2
Scopus rating (2011): SJR 3.47 SNIP 1.634 CiteScore 3.99
ISI indexed (2011): ISI indexed yes
Web of Science (2011): Indexed yes
BFI (2010): BFI-level 2
Scopus rating (2010): SJR 3.395 SNIP 1.421
Web of Science (2010): Indexed yes
BFI (2009): BFI-level 2
The ability to see and manipulate objects with ever decreasing size in a microscope is paramount to the ongoing development of many areas of modern science and technology, from microelectronics to biology and life sciences. The project goal is to demonstrate a technique enabling to image low-contrast nanoscale biological objects in real time without the need for scanning, fluorescent labelling, or fixation. Such a technique can have as great an impact as the invention of the optical microscope itself.

The project goal is achieved by using artificially engineered metal-dielectric nanostructures (hyperbolic metamaterials) with a unique ability to recover information contained in light waves coming from the object's subwavelength features. This is contrary to conventional optical systems where the loss of this information limits the resolution. The central idea of the project is engineering the metamaterial so that only the subwavelength information is transmitted, while any other (background) radiation is filtered out, leading to contrast enhancement similar to the dark-field microscopy. As a result, we would combine superior image resolution (a property of hyperbolic metamaterials) and high image contrast (the result of "dark-field" background filtering). This will be highly desirable for label-free biological imaging scenarios, where faint, weakly scattering objects are abundant. The project aims to verify the concept through direct experimental realization.
Takayama, Osamu (Intern)
Shkondin, Evgeniy (Intern)
Phd Student:
Repän, Taavi (Intern)
Project Manager, academic:
Lavrinenko, Andrei (Intern)

Relations
Publications:
Dark-field hyperlens for high-contrast sub-wavelength imaging
Dark-field hyperlens: Super-resolution imaging of weakly scattering objects
Operator approach to effective medium theory to overcome a breakdown of Maxwell Garnett approximation
Highly doped InP as a low loss plasmonic material for mid-IR region

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
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Amount: 5,756,400.00 Danish Kroner
Project