Functional Metamaterials

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Optical metamaterials are artificial composite materials of tailored nanostructured metallodielectric subwavelength building blocks. As such they can exhibit electromagnetic properties inaccessible in nature, including magnetism at optical frequencies, negative refractive index, perfect absorption, giant circular dichroism and enhanced nonlinear optical properties. The overarching science vision of this project is to create metamaterials with tuneable and enhanced nonlinear properties for use in complex photonic circuitry and advanced photonic signal processing. To achieve this vision we focused our research activities in three sub-programs:

Nonlinear optics in metamaterials: Investigate novel nonlinear processes in metamaterials for optical switching, frequency conversion, and spontaneous generation of light.

Tuneable and active metamaterials: Enable dynamic tunability of the optical properties of metamaterials, as well as to empower them with gain.

Three-dimensional metamaterials: Develop three-dimensional (3D) photonic metamaterials for full 3D control of light flow and polarisation, using designs based on transformation optics.

This project brings together six CUDOS nodes adding complimentary expertise in theoretical analysis, experimental characterisation and nanofabrication. Close collaborative links have been established between the different groups, combining exchange of ideas, novel fabrication and characterisation techniques. For example, the ANU, Swinburne and RMIT nodes are actively collaborating on the experimental aspects of the project, while Sydney, MQ, UTS and ANU are closely involved in the development of theoretical ideas and modelling of metamaterials. The research on the project is enhanced by the active involvement of three PIs and three international Associate Investigators. Close collaboration with Imperial College resulted in the establishment of a PhD student exchange program between CUDOS and Imperial College London in metamaterials research.

Progress

In 2011 we focused on exploratory science to establish the opportunities that metamaterials offer for enhancement of light matter interaction. We also established the required knowledge base and infrastructure for the project, including new analytical and numerical techniques, as well as new fabrication and characterisation tools in the different CUDOS nodes. The team has achieved great progress towards the long term goals of the project, with particular substantial progress in the following areas:

Hamiltonian theory of metamaterials with loss and strong dispersion

In a highly collaborative project with PI Sipe (University of Toronto) we are applying a Hamiltonian approach to develop a systematic method to derive coupled mode equations for waveguides which involve negative index materials. This is a difficult problem since these materials are strong dispersive and very lossy. The developed method will be applied to the description of nonlinear processes in negative index materials, such as high-intensity pulse generation and frequency conversion.

Magnetoelastic metamaterials

Nonlinear phenomena in metamaterials attracts growing interest, however the current approaches utilise a nonlinear response of a single element, which is enhanced through their resonant properties. The structure of the metamaterial remained fixed in such studies. At the same time, the CUDOS team recently reported that structural changes in metamaterials offer an excellent means to control their properties, with a remarkable effect on the resonance position. We therefore sought to combine these ideas through a dynamic structural response, and successfully reached this goal with the development of novel magnetoelastic metamaterials.

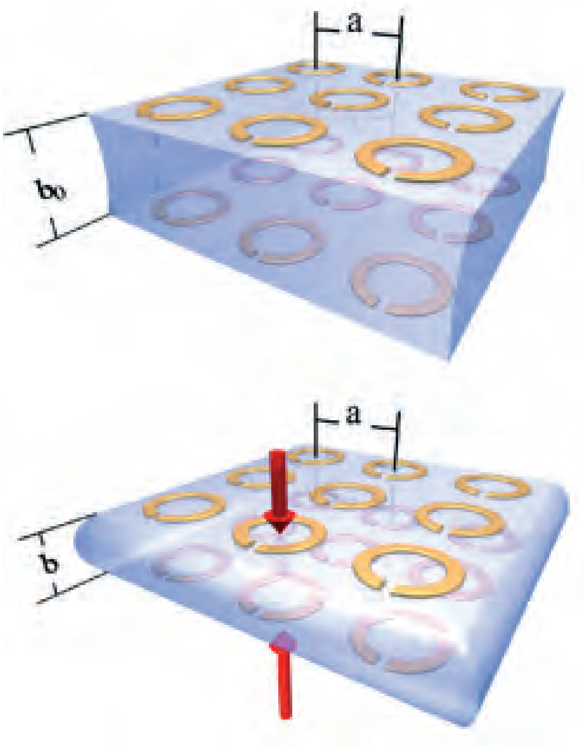

Figure 1: Two layers of the bulk sample are shown. (top) The metamaterial before the electromagnetic field is applied. (bottom) The metamaterial is compressed by the electromagnetic forces acting between the elements, leading to effective nonlinear response.

Within the Nonlinear Metamaterials stream of the Functional Metamaterials project our team proposed and experimentally demonstrated a novel type of nonlinearity in metamaterials, which is induced by mechanical deformation of the structure. The nonlinearity arises from the introduction of an extra degree of freedom in a metamaterial, which allows for elastic displacement of the structural elements. This type of nonlinearity relies on the counter-play between the electromagnetic attraction and the elastic repulsion, and the induced deformation alters the electromagnetic response of the entire structure, leading to the novel nonlinear response of the metamaterial.

As a practical example one can consider an artificial magnetic metamaterial assembled with subwavelength resonators arranged in an anisotropic lattice with elastic properties, and analyse nonlinear phenomena resulting from the self-induced structural changes. We showed that the dependence of magnetization on the incident field intensity and frequency is remarkably nonlinear, giving rise to unusual bistability patterns.

We confirmed experimentally the plausibility of the predicted effects by measuring an intensity-dependent change of the resonance properties in a model system of two resonators, where the elasticity was provided with thin keratin filaments. The measurements are in a good agreement with the corresponding theory.

Engineered metal nonlinearities

Researchers from CUDOS in collaboration with University of Southampton – PI Zheludev have demonstrated that periodic nanostructuring in the form of optical metamaterials can enhance the optical nonlinearity of plasmonic metals by several orders of magnitude. By patterning a gold film, the research team has demonstrated the largest, to date, sub-100 femtosecond nonlinearity, which is suitable for terahertz bandwidth all-optical data processing, as well as ultrafast optical limiters and saturable absorbers.

Liquid crystal tunable metamaterials

One of the most fascinating properties of metal-dielectric structures is the ability to engineer artificial magnetic resonances at optical frequencies. The implementation of metal-dielectric structures exhibiting artificial magnetism such as split-ring resonators and fishnet metamaterials can result in a completely new class of phenomena, such as ultra-high sensitivity to light intensity. The development of materials with this kind of optical functionality is an important milestone in the Functional Metamaterials project as they can be applied to future photonic devices for communication technologies.

In the research development of metamaterials highly sensitive to light intensity we fabricated fishnet metamaterials operating at optical wavelengths [see Fig. 2(a)]. The negative index in such fishnet structures arises due to the interplay of the hole-modes (defining the electric permittivity) and the anti-symmetric gap plasmon modes (defining the magnetic permeability). Importantly, either of these modes can be affected by altering the refractive index of the dielectric layers. Therefore, the incorporation of nonlinear dielectric materials inside the holes of the fishnet or between its metal plates can result not only in large transmission change, but also in variation of the effective metamaterial refractive index.

Functional Metamaterials Continued

Experimentally, we infiltrated the fishnet metamaterial structures with nematic liquid crystal (LC) and used external fields (DC or optical) to control the orientation of the LC molecules. The fishnet samples were prepared with vertically pre-orienting LC molecules and an infrared laser beam illuminated the sample from the substrate side. As the incident laser power increased we observed a drop (sub-linear dependence) in the light transmission. At low input powers we measured transmission through the infiltrated structure of around 7%. When the input laser power was increased, we observed a reduction in this transmission of approximately 30% [Fig. 2(b)]. We also found that the measured nonlinear transmission change was dependent on the application of vertical bias DC electric field, indicating again that a strong molecular re-orientation of the LC has occurred inside the holes of the fishnet metamaterials.

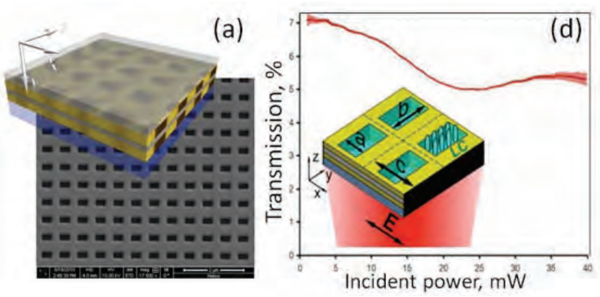

Figure 2: (a) Fabricated fishnet metamaterials and (b) measured dependence of light transmission through the fishnet metamaterials on the incident laser power.

Our results demonstrate fivefold enhancement of the nonlinear properties of the fishnet metamaterials and appear attractive for application in ultra-low power optical switching.

Nonlinear chiral metamaterials

By combining strong chirality and the nonlinearity of metamaterials we developed a metamaterials structure with nonlinear optical activity— a polarisation rotation that depends on the strength of the incident field. This effect is almost negligible in natural crystals and has therefore not yet been used for real-life applications. Using metamaterials, such effect can be achieved by engineering the chiral response and carefully placing nonlinear elements within the structure. The fabricated structure consists of a pair of metallic wires, twisted so that they are no longer parallel. Nonlinearity is introduced by cutting each wire and inserting a varactor diode in the middle.

The response of the structure exhibits a strongly resonant feature caused by the excitation of currents in the left-handed metamolecule by the left-handed circularly polarised wave. At the same time, the right-handed circularly polarized wave does not noticeably excite any resonances in the structure. Changing the power of the incident wave shifts the resonance of the gyrotropic response to a higher frequency. Importantly, such a shift of the polarisation rotation resonance leads to a giant nonlinear gyrotropy. Our experimental results indicated a peak value of 15 deg/W, which is 12 orders of magnitude stronger than results previously observed for $LiIO_3$ at optical wavelengths.

Gyroid networks for 3D metamaterials

During 2011 we experimentally realised a novel class of chiral photonic microstructures using direct laser writing. These structures, called gyroids represent a class of cubic chiral srs-networks and have a design that was inspired by recent theoretical findings of circular dichroism bands in the wing-scales of a butterfly. These cubic chiral srs-networks exhibit circular dichroism in the near-to create true 3D metamaterials.

We recently fabricated very small (around 100 nm periodicity) double gyroid - achiral microstructure composites in a polymer photoresist, which when metalized are known to exhibit a negative refractive index in a nearly isotropic 3D metamaterial. These metamaterials rely on the interaction between the two intertwining networks to form propagating modes at the long wavelength, metamaterial regime.

These chiral srs-networks make also for interesting designs for microwave metamaterials. Large scale structures made via 3D printing method in gypsum can be used for quick prototyping of a 3D chiral microwave metamaterial, in which strong optical activity is expected when coated with a metal.

Highlights

- We were delighted to have Prof Sir John Pendry, a pioneer of the field of metamaterials, visit us in July 2011. This was an inspiring visit with fruitful discussions as seen in the adjacent photograph. The culmination of the visit was the signing of the CUDOS-Imperial College London metamaterials PhD student exchange program, where two students from ANU and RMIT have already been selected to visit Imperial College.
- During the year I. Shadrivov and B. Jia visited the University of Southampton. Both visits, supported by the Australian Academy of Science, enhanced the collaboration with PI Zheludev and substantially advanced our understanding of nonlinear metamaterials.

Discussions with Sir J. Pendry in July 2011 at the University of Sydney, covering different aspects of metamaterials research, including novel metamaterials geometries

- The achievements of three CUDOS CIs in the field of metamaterials were acknowledged by the recently established Nature Publishing Group journal NPG Asia Materials with an invitation to write a review on metamaterials and meta-optics. The review (see figure below) covered a large scope of topics and highlighted the achievements of the Functional Metamaterials program in this prestigious Nature-associated journal.

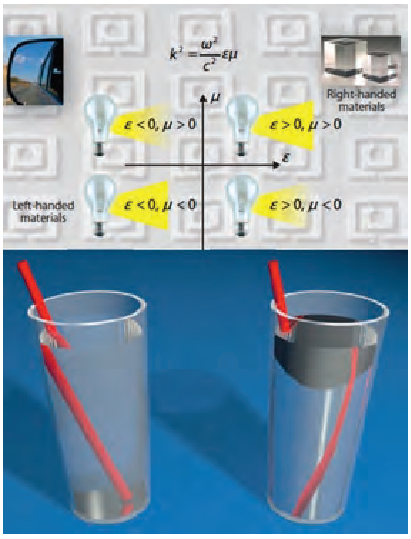

Figure 3: (top) The regions of possible permittivity (ε) and permeability (μ), showing normal refraction (top right) and negative refraction (bottom left). (bottom) Normal refraction (left) and left-handed refraction (right).

- The outcomes of the Functional Metamaterials project were reported in 13 journal publications where more than four of them have been in journals with impact factor higher than six, including Nature Materials, Physical Review Letters, Advanced Materials, Laser & Photonics Reviews, and NPG Asia Materials. A highlight of these publications was the work on Magnetoelastic metamaterials published in Nature Materials with IR=30. This work received a significant media coverage, including a large amount of internet sites and local radio: http://www.abc.net.au/science/articles/2011/11/14/3363105.htm
- Dr. A. Miroshnichenko, ANU was awarded a Future Fellowship by the Australian Research Council. He will work on hybrid approaches for low-loss metamaterials.

Future Directions

Having established a significant knowledge base in optical and infra-red metamaterials, state of the art nanofabrication and optical characterisation, our team is in a strong position to target the demonstration of novel nonlinear optical effects in metamaterials. A strong emphasis in the 2012 program is put on the development of novel three-dimensional metamaterials. The practical realisation of such metamaterials will enable us to demonstrate bulk nonlinear optics in metamaterials and will open the doors towards our science vision with integration of metamaterials components on a photonic chip.

Project Leader

Dragomir Neshev received the Ph.D. degree in physics from Sofia University, Bulgaria in 1999. Since then he has worked in the field of nonlinear optics at several research centres around the world. Since 2002, he has been with the Australian National University, where he is currently Associate Professor and leads the Experimental Photonics group at the Nonlinear Physics Centre. He is the recipient of a number of awards, including a Queen Elizabeth II Fellowship (ARC, 2010) an Australian Research Fellowship (ARC, 2004), a Marie-Curie Individual Fellowship (European Commission, 2001), and the Academic award for best young scientist (Sofia University, 1999). His activities span over several branches of optics, including nonlinear periodic structures, singular optics, plasmonics, and photonic metamaterials.