METAMATERIAL NEMS: GIANT OPTICAL NONLINEARITY AND MAGNETOELECTRIC EFFECT

João Valente[1], Jun-Yu Ou[1], Eric Plum[1], Kevin F. Mac Donald[1], Nikolay Zheludev[1,2]
[1] Optoelectronics Research Centre and Centre for Photonic Metamaterials, University of Southampton, United-Kingdom
[2]Centre for Disruptive Photonic Technologies, Nanyang Technological University, Singapore
E-mail: jpv1f11@soton.ac.uk

ABSTRACT

We report NEMS-based reconfigurable photonic metamaterials controlled by electrical currents, magnetic fields and light. Our structures provide practically useful solutions for sub-megahertz and high contrast magnetoelectric modulation of metamaterial optical properties and a cubic optical nonlinearity that is ten orders of magnitude greater than the reference nonlinearity of CS_2.

OPTICAL NEMS METAMATERIALS

Metamaterials offer a large range of novel or enhanced optical properties, however, they are usually narrow-band and fixed. Thus, dynamic control over metamaterial properties has become a major challenge.

A practical and low power solution for tuning metamaterial optical properties is inspired by NEMS technologies and concepts. Reconfigurable plasmonic metamaterials exhibit tunable or switchable optical properties that are controlled by dynamically rearranging the components of the metamaterial array. This deformation of the nanostructure is achieved by supporting the metamaterial building blocks with an elastic structure that moves in response to electrical fields or ambient temperature changes [1-2]. Here we demonstrate for the first time reconfigurable plasmonic metamaterials driven by electrical currents, magnetic fields and light.

Optically Reconfigurable Metamaterial

We experimentally demonstrate for the first time that light can control light in a plasmonic metamaterial using nonlinearity of nanooptomechanical nature. As illustrated by Figure 1(a), the metamaterial consists of Π-shaped gold resonators known for plasmon-induced transparency. Horizontal and vertical parts of the resonators are 50 nm thick and have been supported by different flexible silicon nitride bridges of 50 nm thickness to allow for relative movement. Maxwell stress tensor calculations reveal optical forces acting between the gold resonators supported by separate bridges in response to optical excitation near the structure's 1240 nm absorption resonance, see Figure 1(b).

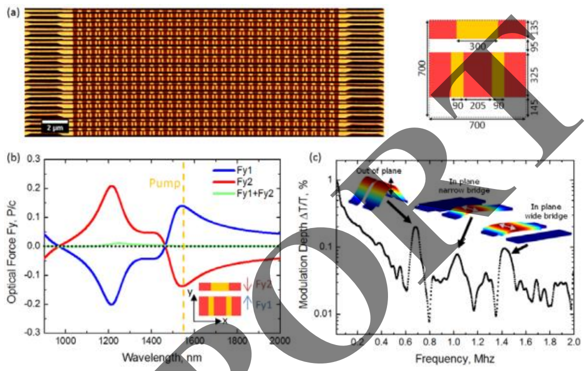

Figure 1. (a) Scanning electron microscope image of an optically reconfigurable metamaterial, Au (yellow) plasmonic resonators supported by free-standing Si_3N_4 bridges (red). The inset shows an individual unit cell with lengths marked in nm. (b) Simulated optical forces between the bridge segments of an individual 700 × 700 nm^2 unit cell acting in the metamaterial plane. P is the incident power per unit cell and c is the speed of light in vacuum. The dashed line indicates the 1550 nm optical pump wavelength. (c) Observation of light-by-light modulation: Modulation depth as a function of modulation frequency for a pump power of 0.66 mW, with mechanical eigenmode simulations shown as insets.

Pumping the nanostructure with a modulated laser beam at 1550 nm, where simulations predict significant relative optical forces (along y), optomechanically induced modulation of the metamaterial's transmisison was probed at 1310 nm. As shown by Figure 1(c), pumping of the metamaterial leads to a modulation of the metamaterial's transmission, which is largest at low frequencies and at several resonances at MHz frequencies. Both near-field optical forces and differential thermal expansion of gold and silicon nitride due to optical heating will contribute to out-of-plane oscillations of the bridge beams (inset Figure 1(c)). However, the metamaterial's in-plane mechanical oscillations at 1 MHz and 1.4 MHz cannot be explained by heating of the nanostructure, providing strong evidence that the deformation of the nanostructure is driven by near-field optical forces between the plasmonic resonators. We observe a linear dependence of the transmission modulation on the pump intensity, which can be described by the first nonlinear absorption coefficient β. Assuming that the nonlinear transmission change ΔT results from nonlinear absorption, $\beta \sim \Delta T/(It)$, where I is the intensity and t is the metamaterial thickness. In the low frequency limit $\beta\sim10^{-2}\ m/W$, which exceeds the nonlinearity of CS_2 by 10 orders of magnitude.

Magnetoelectrically Reconfigurable Metamaterial

For the first time we demonstrate a reconfigurable metamaterial controlled by currents and magnetic fields, offering solutions that provide high-contrast modulation of optical properties at up to 100s of kHz, while integrating easily in optoelectronic devices. Here, we dynamically rearrange the entire metamaterial array by exploiting the magnetic Lorentz force associated with electrical charges moving in a magnetic field and differential thermal expansion of bimorph metamaterial components resulting from resistive heating. The associated optical manifestations correspond to an exceptionally large and novel optical magnetoelectric effect.

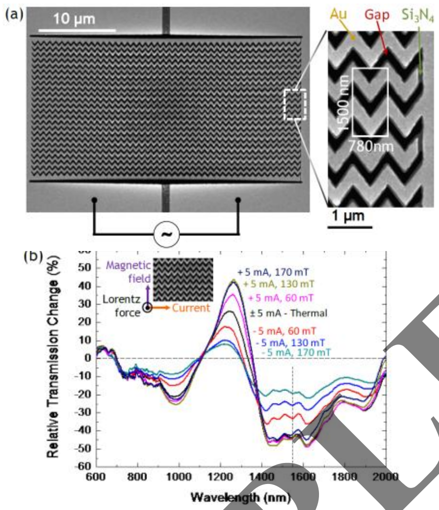

Figure 2. (a) Structure of the reconfigurable photonic metamaterial consisting of free-standing plasmonic zig-zag shaped bridges, where every second bridge is connected to electrical terminals on both ends, see close-up of the bridges ends. (b) Magnetic tuning of the reconfigurable photonic metamaterial. Relative transmission change as a function of applied device current and magnetic field.

As illustrated by Figure 2(a), the metamaterial consists of elastic zig-zag bridges manufactured from a bilayer of 50 nm of gold on 50 nm of silicon nitride. Every second bridge is electrically connected to electrical terminals on both ends. Application of a current of 5 mA to the device leads to resistive heating of the electrically connected bridges, which bend due to differential expansion leading to transmission changes of up to 50%, see black curve in Figure 2(b). Simultaneous application of a magnetic field in the metamaterial plane and perpendicular to the current flow leads to a Lorentz force that increases/decreases the mechanical deformation depending on the relative directions of current flow and magnetic field, leading to an increase/decrease of the electrothermal transmission modulation, which is particularly apparent around 1250 nm wavelength. Detailed measurements show that the electrothermal modulation of the nanostructure is limited by its thermal cooling timescale and can be driven up to modulation frequencies of 10s of kHz, while magnetic modulation can be driven up to the nanostructure's fundamental mechanical resonance at about 400 kHz.

CONCLUSION

In summary, we demonstrate the first plasmonic metamaterials exhibiting a giant optical nonlinearity and magnetoelectric effect driven by mechanical deformation of the metamaterial structure.

The optically nonlinear metamaterial is driven by electromagnetic near-field interactions and thermo-optical effects that can overcome elastic forces: light intensities of only a few $\mu W/\mu m^2$ can reconfigure the metamaterial array of plasmonic metamolecules leading to a significant change of its optical properties. This new type of nonlinearity has a resonant character and can provide light-by-light modulation with MHz bandwidth.

The magnetoelectrically reconfigurable metamaterial demonstrates the fastest and most practical solutions for large-range tuning of reconfigurable photonic metamaterials so far: (i) Electrothermal modulation at up to 10s of kHz exploiting local resistive heating and differential thermal expansion and (ii) magnetic modulation up to 100s of kHz and beyond exploiting the Lorentz force on current-carrying reconfigurable parts of the metamaterial which is placed in an external magnetic field.

REFERENCES

[1] [1] A. Q. Liu, W. M. Zhu, D. P. Tsai and N. I. Zheludev, “Micromachined tunable metamaterials: a review,” J. Opt., vol. 14, p. 114009, 2012.

[2] J. Y. Ou, E. Plum, J. Zhang, and N. I. Zheludev, "An electromechanically reconfigurable plasmonic metamaterial operating in the near-infrared," Nature Nanotech., vol. 8, p. 252-255, 2013.