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Switching Near-IR Metamaterial Response with Electrically-Controlled Liquid Crystals

O. Buchnev [1,2], J. Y. Ou [1,2], M. Kaczmarek [3], N. I. Zheludev [1,2,4], V. A. Fedotov [1,2]

[1] Optoelectronics Research Centre, University of Southampton, SO17 1BJ, UK
[2] EPSRC Centre for Photonic Metamaterials, University of Southampton, SO17 1BJ, UK
[3] School of Physics and Astronomy, University of Southampton, SO17 1BJ, UK
[4] Centre for Disruptive Photonic Technologies, Nanyang Technological University, 637371, Singapore
e-mail: o.buchnev@soton.ac.uk

Abstract – **We experimentally demonstrate efficient electrical modulation and switching of the near-IR response of plasmonic metamaterials loaded with liquid crystals. That has been achieved by controlling micro-scale volume and (for the first time) nano-scale in-plane ordering of liquid crystals in the resulting hybrid metamaterial systems.**

I. Introduction

Metamaterials have rapidly advanced over the past few years and are now expected to have major impact across the entire field of photonics. The current effort of the world's leading metamaterial labs is being focused on implementing the idea of active and switchable metamaterials, a new generation of artificial photonic media with dynamically controlled optical properties. The latter is perceived as the next important stage in the development of the metamaterial concept, which would make metamaterials the fundamental base of future photonic devices [1]. The control of optical properties in such metamaterials can be achieved by either mechanically changing their fabric through MEMS [2] or deformations [3, 4], or hybridizing their structure with the available nonlinear or functional media. One of the prime contenders currently emerging for the hybridization is liquid crystals.

While electrical control of liquid crystal properties has been exploited for tuning negative-index microwave metamaterials [5, 6] as well as nonlinear optical metamaterials [7], to the best of our knowledge we report the first demonstration of efficient electrical modulation and switching of the near-IR response of plasmonic metamaterials, which was achieved by controlling micro-scale volume and (for the first time) nano-scale in-plane ordering of liquid crystals in the resulting hybrid metamaterial systems.

II. Switching Metamaterial Through Volume LC Ordering

Switching metamaterial response engaging micrometer-scale volume ordering of liquid crystals was achieved by integrating metamaterial into a twisted LC cell. The resulting hybrid cell was comprised of a 15 μm thick layer of nematic liquid crystal E7 confined between the metamaterial and a transparent electrode coated with LC-alignment layer, as show in Fig. 1a. The structure of the metamaterial was formed by a continuous zig-zag wire nano-pattern, which was milled using focused ion beam in a 80 nm thick gold film deposited on a glass substrate (see inset to Fig. 1a). Direct contact of the liquid crystal with the nano-structure provided anchoring and aligned LC molecules orthogonal with respect to the molecules at the transparent electrode leading to the twisted ordering in the nematic phase.

While the continuous metallic fabric of the metamaterial served as the second electrode, its polarization sensitive resonance determined the optical response of the entire hybrid cell. In particular, the resonant polarization of incident light (i.e. polarization that coupled to the plasmonic excitations in the nano-structure at ~1.5 μm) became non-resonant while propagating in the twisted cell and was transmitted. By applying electric field of up to 7 V across the cell we could reversibly destroy the twisted state and reduce transmission of the metamaterial at its resonance by a factor of five (see Fig. 1b).

We also note that in the resulting hybrid optical cell the metamaterial nano-structure replaced all three essential components of an LC device: (i) LC-alignment layer; (ii) transparent electrode and (iii) polarizer;

making the hybrid cell more compact than the conventional LC devices and thus easy to integrate into plasmonic and nano-photonic circuits.

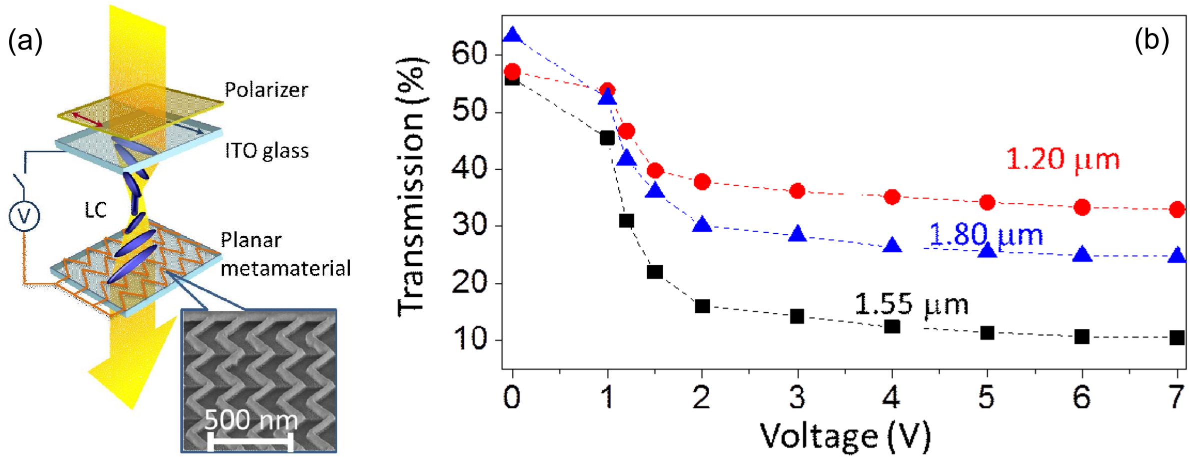

Fig. 1. (a) Design of a hybrid metamaterial-based liquid-crystal optical cell. Inset shows SEM micrograph of the fabricated continuous-wire plasmonic metamaterial array. (b) Transmission of the metamaterial-liquid-crystal hybrid cell as a function of applied voltage for several wavelengths near the metamaterial resonance.

III. Switching Metamaterial Through In-Plane LC Ordering

Metamaterial switching due to nanometer-scale in-plane ordering of liquid crystals was demonstrated for a substrate-free complimentary (i.e. negative) version of the zig-zag metamaterial. It was milled in an 80 nm thick gold film using focused ion beam and was suspended on 100 nm thick silicon-nitride bridges (see Fig. 2a). The absence of the substrate material in the gaps between the zig-zag elements of the metamaterial network substantially reduced the anchoring of the LC-molecules, permitting their reorientation in the gaps under electric field applied in the plane of the nano-structure.

Near-IR resonant response of the nano-structure corresponded to a transmission peak at around 1.2 μm, which become red-shifted by about 0.3 μm upon hybridization of the metamaterial with nematic liquid crystal E7 (see Fig. 2b). The control in-plain electric field was produced by applying voltage across the gaps in the range from 0 to 2.7 V.

Depending on the level of the applied voltage we noted two distinct regimes of metamaterial switching. The first regime was observed below 1.5 V. It corresponded to a change in the magnitude of the metamaterial transmission (see Fig. 2b) and was attributed to volume ordering of the liquid crystal in a layer directly above the nano-structure. The second regime was engaged by increasing the control voltage above 1.5 V. It was characterized by a red shift of the transmission resonance (see Fig. 2c), which resulted directly from the reorientation of LC-molecules in the gaps of the metamaterial nano-structure.

IV. Conclusion

We experimentally demonstrated efficient electrical modulation and switching of the near-IR response of plasmonic metamaterials hybridized with liquid crystals by controlling micro-scale volume and nano-scale in-plane ordering of LC-molecules in the resulting hybrid metamaterial systems. Furthermore, we showed that metamaterial nano-structure can replace all three essential components of a conventional LC device, namely LC-alignment layer; transparent electrode and polarizer; making the metamaterial-based optical cell more compact and easy to integrate into plasmonic and nano-photonic circuits. The relative ease of on-demand engineering resonant bands (i.e. colours) and tailoring reflection/refraction phenomena in metamaterials would be particularly appealing for application in high-resolution and emerging display technologies including near-to-eye and virtual retina displays, holographic and 3D imaging.

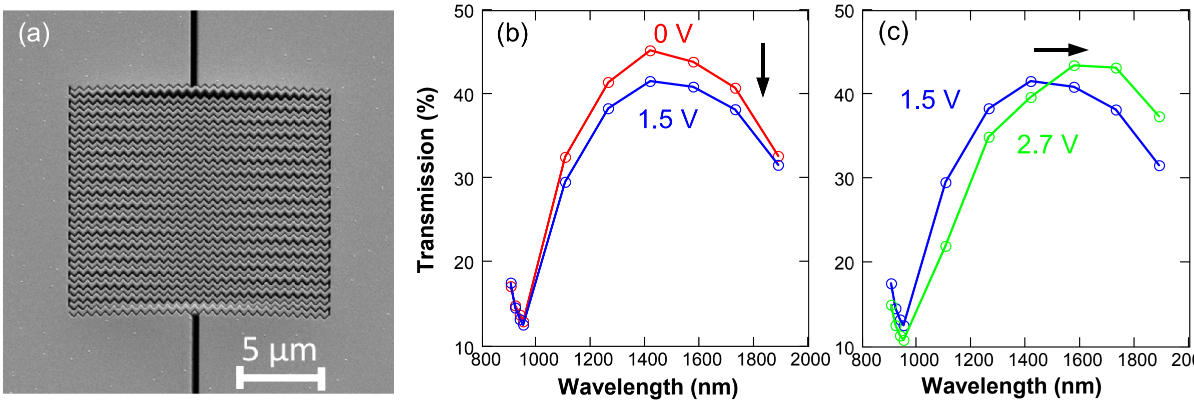

Fig. 2. (a) SEM micrograph of a plasmonic metamaterial with its metalic zig-zag network suspended on the nano-scale bridges milled in a silicon nitride membrane. Panels (b) and (c) show changes of the metamaterial transmission spectrum for different levels of the control voltage after the structure was hybridized with a liquid crystal.

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