Electrically Controlled Liquid Crystal Plasmonic Metamaterials

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In this work we experimentally demonstrate high-contrast electrical modulation of the near-IR spectra of plasmonic metamaterials, hybridised with liquid crystals by exploiting volume and, for the first time, in-plane switching regimes. We also show that in the resulting hybrid liquid-crystal (LC) optical cells the metamaterial structure can replace all three essential components of a LC device, namely (i) LC-alignment layer; (ii) transparent electrode and (iii) polarizer; making the hybrid cell much more compact than the conventional LC devices and easy to integrate with plasmonic and nano-photonic circuits. The relative ease of on-demand engineering of resonant bands (i.e. colours) in plasmonic nano-structures is particularly appealing for applications in high-resolution and emerging micro-display technologies, such as near-to-eye and virtual retina displays.

For achieving efficient electrical control of the metamaterial response using volume switching of liquid crystals we combined a nano-structured planar metamaterial with a twisted LC cell, as shown in Figure 1a. Such hybrid cell comprises of a 15 µm thick layer of nematic liquid crystal, which is confined between the metamaterial nano-structure and a transparent electrode, coated with the LC-alignment layer. The planar metamaterial was fabricated by ion-beam milling of an 80 nm thick gold film deposited on a glass substrate. We found that the direct contact of the liquid crystal with the surface of the resulting nano-structure provides both the anchoring and alignment for the LC molecules at the bottom of the cell in such a way that they align orthogonal with respect to the molecules at the top of the cell. Due to elastic forces in the nematic phase, the twisted ordering of the mesogenes is formed in the bulk of LC, making the hybrid cell optically active.

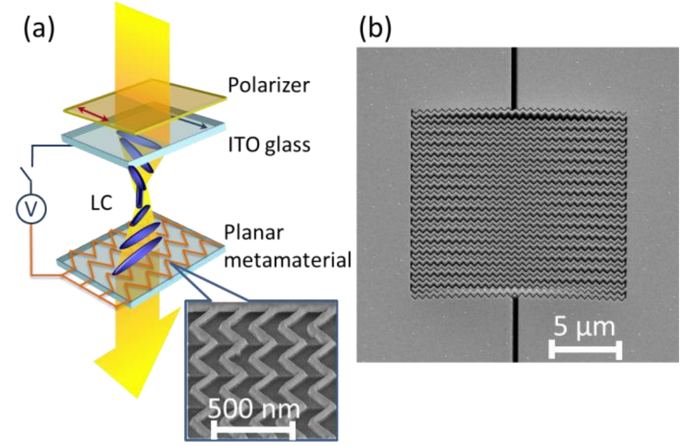

Figure 1. (a) Design of a hybrid metamaterial-based liquid-crystal optical cell. Inset shows SEM micrograph of the fabricated metamaterial array taken at 52° to the array's normal. (b) SEM micrograph of a plasmonic metamaterial with its metalic zig-zag network suspended on bridges milled in a silicon nitride membrane.

While the continuous zig-zag metallic network of the metamaterial structure serves here as the bottom electrode, its polarization sensitive plasmonic resonance determines the optical response of the entire hybrid cell. In particular, the resonant polarization of the incident light (i.e. polarization that couples to the plasmonic excitations in the nano-structure) becomes non-resonant following 90° rotation in the twist cell and is therefore transmitted. However, this will be substantially attenuated within the resonant band of the metamaterial as soon as electric field is applied across the cell, destroying its twisted state. In our experiments, the hybrid cell showed a fivefold hysteresis-free modulation of transmission at the metamaterial resonance wavelength of 1.55 µm with the control signal of only 7 V.

The in-plane switching of the metamaterial response was demonstrated using a suspended negative version of the metamaterial nano-structure. Its metallic network was supported by silicon nitride bridges, which were milled in a 100 nm thick silicon nitride membrane during the fabrication of the metamaterial (see Figure 1b). The absence of the substrate material in the gaps between the zig-zag elements of the metamaterial array enabled to substantially reduce the anchoring of the LC-molecules, permitting reorientation of the latter in the gaps while applying electric field in the plane of the nano-structure. In our experiments the in-plane switching mode allowed us to decrease the operating voltage to ~1.5 V, thus reducing the size of the switching region engaging the LC layer of only about 200 nm thick.

Given the wide range of exotic photonic functionalities demonstrated by plasmonic metamaterials and also their potential to replace bulk optical components, we envisage a whole new generation of extremely compact metamaterial-based liquid-crystal cell switchers and modulators and other photonic components exploiting electro-optical control.