Electro-optical control in a plasmonic metamaterial hybridised with a liquid-crystal cell

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Abstract: We experimentally demonstrate efficient electro-optical control in an active nano-structured plasmonic metamaterial hybridised with a liquid-crystal cell. The hybridisation was achieved by simultaneously replacing the polarizer, transparent electrode and molecular alignment layer of the liquid-crystal cell with the metamaterial nano-structure. With the control signal of only 7 V we have achieved a fivefold hysteresis-free modulation of metamaterial transmission at the wavelength of 1.55 µm.

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Metamaterials in optics represent a large class of nano-structured artificial media with optical characteristics unavailable, or superior, to those exhibited by natural materials [1–3]. Since the experimental demonstration of exotic negative refraction [4] the metamaterial concept has been widely exploited by the scientific community enabling, in particular, enhanced polarization control [5–8], absorption [9–11], asymmetric transmission [12–14], cloaking [15–17], slow light [18, 19], and novel sources of coherent radiation [20, 21]. Some of these fundamental studies have already resulted in substantial improvement of existing photonic devices and applications. Recent examples of practical implementation of the metamaterial concept include broadband circular polarizer [22, 23], polarization spectral filter [24], and refractive-index sensor [25].

In this letter we experimentally demonstrate electro-optical control using an active nano-structured plasmonic metamaterial hybridised with a liquid-crystal cell. We show that in such a hybrid device the metamaterial nano-structure can replace all three essential components of the conventional liquid-crystal (LC) cell, namely: (i) liquid-crystal alignment layer; (ii) transparent electrode; and (iii) polarizer; simultaneously providing resonant spectral selectivity in the optical response of the cell. While electrical control of liquid crystal

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properties has been exploited for tuning negative-index microwave metamaterial [26, 27] and nonlinear optical metamaterials [28], to the best of our knowledge we report the first demonstration of high-contrast electro-optical modulation in an LC-based active metamaterial structure in the optical part of the spectrum.

Figure 1 illustrates the design and operation principle of the hybrid metamaterial-LC cell. The cell comprises a layer of nematic liquid crystal, which is confined between a planar metamaterial and a transparent electrode coated with the LC-alignment layer. Direct contact with the metamaterial nano-structure provides anchoring and alignment for the LC molecules at the bottom of the cell in such a way that they reside perpendicular 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, making the LC cell optically active.

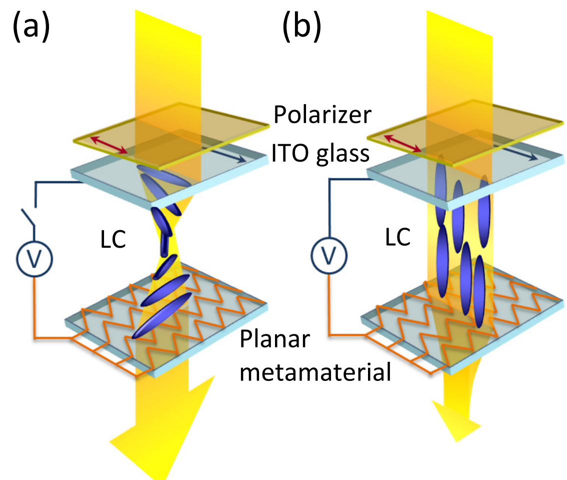

Fig. 1. Design and operational principle of a hybrid metamaterial-based liquid-crystal optical cell. Panels (a) and (b) show the hybrid cell in the OFF (twisted) and ON (homeotropic) states correspondingly.

Consequently, the polarization azimuth of linearly polarized light propagating through this medium rotates, and in the case of an optically thick twisted cell (tens of microns) adiabatically follows the LC-director (see Fig. 1(a)). The liquid crystal configuration set by the surfaces can be changed and adjusted by applying an electric field across the cell, which distorts the ordering of LC molecules in its volume and switches the cell from the twist to the so-called homeotropic configuration. Such configuration appears isotropic in the direction of light propagation and therefore does not perturb the incident polarization state (see Fig. 1(b)). While the 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, light with resonant incident polarization, i.e. polarization that couples to the plasmonic excitation, will be substantially attenuated within the engineered resonance band in the planar cell (see Fig. 1(b)), and transmitted by the twisted cell, since the polarization state becomes non-resonant following a 90° rotation, as illustrated in Fig. 1(a).

In principle, the functionality of the hybrid metamaterial-LC cell can be enhanced further by introducing a second plasmonic metamaterial, which would also replace the remaining top polarizer, electrode and alignment layer. However, in our proof-of-concept demonstration with basic electro-optical switching in the near-IR spectral range the hybrid cell will contain only one metamaterial structure, as illustrated in Fig. 1.

Our planar metamaterial structure was based on a continuous zigzag-wire pattern rendered by an array of connected V-shaped plasmonic resonators with a 490 nm square unit cell (see Fig. 2(a)). It was milled using a focused ion beam (Helios Nanolab 600) in an 80 nm thick

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gold film deposited on a glass substrate. The fabricated metamaterial sample covered an area of 25.6 μm × 24.2 μm and contained about 2,600 V-resonators. Gold nano-wires forming the resonators had a width of about 80 nm and, as shown in Fig. 2(a), remained electrically connected to the rest of the gold film forming the bottom electrode.

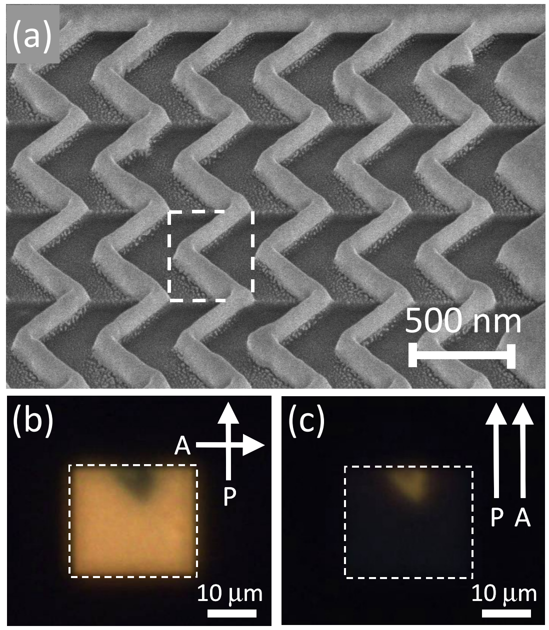

Fig. 2. (a) SEM micrograph of the fabricated metamaterial array taken at 52° to the array's normal. Dashed box indicates a square unit cell of the periodic pattern. Panels (b) and (c) show images of the hybrid liquid-crystal cell made with polarization optical microscope, where arrows indicate mutual orientations of polarizer P and analyzer A. Dashed boxes indicate the area of gold film occupied by the plasmonic metamaterial. The triangular spot at the top of the box corresponds to a nano-fabrication defect.

The transmission response of the fabricated metamaterial was characterised in the 1.0 – 1.9 μm range of wavelengths for two orthogonal linear polarizations using a microspectrophotometer QDI-2010 (CRAIC Technologies) with a sampling area of 10 μm × 10 μm (see Fig. 3(a)). For light polarized along the length of the zigzag nano-wires (non-resonant polarization) our metamaterial was almost transparent featuring a nearly flat transmission spectrum with the average level of ~80%. For the other (resonant) polarization the nano-structure exhibited a well-defined transmission stop-band centred at around 1.2 μm, where the transmission level dropped to about 10%. The stop-band corresponded to the electric dipolar resonance due to $\lambda/2$ mode of standing-wave plasma oscillations induced in the straight sections of all V-resonators. That was confirmed by modelling the near-field distribution in the array's unit cell, using a full 3D Maxwell equations solver COMSOL 3.5a (see insets to Fig. 3(a)). Given the size and anisotropy of the unit cell this plasmonic dipolar mode could only be excited in the near-IR with the electric field of the light parallel to the cell's symmetry axis.

The electro-optical cell was assembled by placing an ITO cover glass (serving as the top electrode) approximately 15 μm away from the metamaterial structure with a slope of about 0.1° to reduce the effect of cavity interference. The surface of the cover glass facing the metamaterial was coated with a thin film of polyimide rubbed in a direction orthogonal to the length of the zigzag-wires, as schematically shown in Fig. 1. The cell was vacuum-filled with E7 (Merck), a widely used and commercially available liquid-crystal mixture.

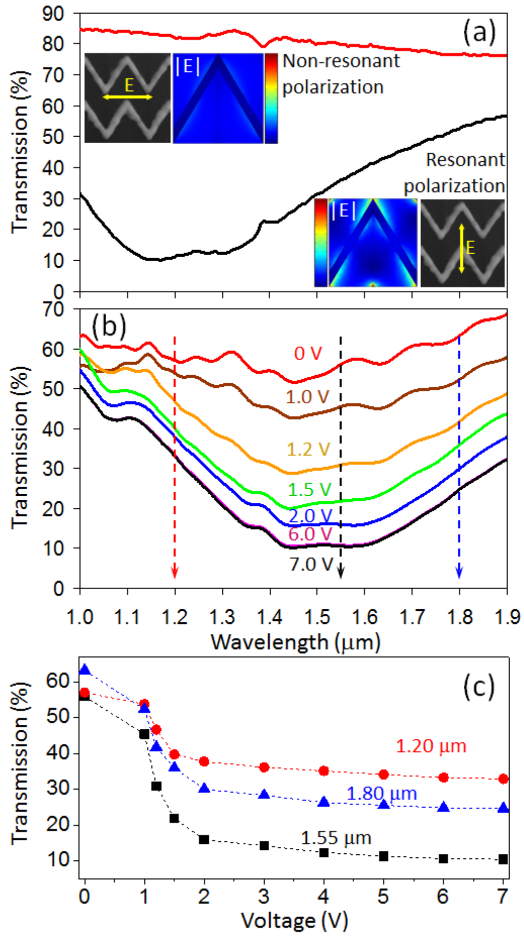

Fig. 3. (a) Transmission spectra of bare metamaterial. Insets show orientations of resonant and non-resonant polarizations with respect to metamaterial structure, and maps of corresponding near-field distributions calculated at 1.2 μm (same colour scale). (b) Transmission spectra of the metamaterial hybridized with a liquid-crystal cell measured for resonant incident polarization at various levels of control signal. (c) Transmission of the metamaterial-liquid-crystal hybrid cell as a function of applied voltage at selected wavelength indicated by dash arrows on the panel (b).

The resulting hybrid liquid-crystal cell showed a twisted state with a uniform, high optical quality. We verified this using a polarizing optical microscope (see Fig. 2(b) and 2(c)). Most of the metamaterial sample appeared bright in transmission when the polarizer and analyser were crossed (Fig. 2(b)), and dark when the two were aligned (Fig. 2(c)). The area corresponding to a small nano-fabrication defect (triangular spot in Fig. 2(b) and 2(c)) showed the opposite behaviour, indicating local transition from twisted to homeotropic ordered liquid crystal, which occurred due to the absence of anchoring at the defect site. Although combining metamaterials and plasmonic structures with liquid crystals has been pursued in a number of works [28–33], the uniform alignment achieved in our hybrid cell is, to the best of our knowledge, the first demonstration of *strong surface ordering of LC molecules* promoted by the metamaterial nano-structure, acting therefore as the alignment layer itself.

Electro-optical control of the metamaterial transmission was demonstrated for the case of resonant incident polarization by applying a voltage between the ITO glass and the metamaterial in the range 0 – 7 V (see Fig. 3(b)). At 0 V the cell was in the twisted state and

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the transmission spectrum was almost flat, corresponding to a non-resonant response of the metamaterial. A shallow transmission dip observed at around 1.5 μm we attribute to a slight deviation of the achieved in-volume LC-ordering from the full 90° twist, when the transition of incident polarization to the non-resonant state was not complete. With increasing voltage the dip was seen to develop further, rendering a transmission stop-band that fully emerged at about 7 V. Clearly, the observed stop-band corresponded to the plasmonic resonance of the metamaterial being red-shifted due to the presence of E7 (estimated shift 0.25 μm), indicating the complete switching of the cell from the twisted to the homeotropic state. At the resonance wavelength, near 1.55 μm we achieved a fivefold hysteresis-free modulation of transmission. The level of modulation is decreasing at the off-resonant wavelengths. For instance, at 1.20 μm and 1.80 μm, the transmission changes by a factor of 1.5 and 2 respectively (see Fig. 3(c)).

In conclusion, we experimentally demonstrated efficient electro-optical control in a nano-structured plasmonic metamaterial hybridized with a liquid-crystal cell. We also showed that the metamaterial nano-structure can simultaneously replace all key components of the cell, such as alignment layers, polarizers and transparent electrodes, thus making the resulting hybrid device much more compact 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 [34] can be particularly relevant for applications in high-resolution and emerging micro-display technologies, such as near-to-eye and virtual retina displays. Given the wide range of exotic photonic functionalities demonstrated by planar metamaterials [35, 36] and also their potential to replace bulk optical components [37–39], a whole new generation of extremely compact metamaterial-based liquid-crystal cell switchers and modulators and other photonic components exploiting electro-optical control can be envisaged.

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