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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