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Active Tuning of High-Q Dielectric Metasurfaces by Liquid Crystals

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Abstract: We demonstrate active tuning of high-Q dielectric metasurfaces by embedding asymmetric silicon meta-atoms in liquid crystals, thus controlling the relative refractive index by heating. Spectral tuning of more than three resonance widths is achieved.

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Many of the possible future applications of metasurfaces depend upon the ability to dynamically tune their optical properties by an external control parameter, such as a small electric field. Examples include tunable flat lenses with dynamic focus, active beam steering, and dynamic holographic displays. However, previous studies of tunable metasurfaces have only achieved minimal tunability, e.g. spectral shift of approximately one resonance width. Here we demonstrate the control of a high-Q ($Q = 270 \pm 30$) dielectric metasurface by changing the properties of the medium surrounding the meta-atoms. We utilize nano-resonators with an asymmetric geometry, which allows for weak coupling to free space [1, 2] and therefore produces high-Q transmission features. To enable the tuning of these high-Q resonances we embedded the metasurface with nematic Liquid Crystals (LCs), where the LC molecules are aligned along one of the principal axes of the resonators. By heating the LCs above the isotropic transition temperature, we can tune the narrow band transmission features of the dielectric metasurface by more than three resonance widths, achieving a figure of merit of $FOM = \Delta\lambda/FWHM = 3.3 \pm 0.6$, where $\Delta\lambda$ is the resonance width and FWHM is its full width at half maximum. Tunable dielectric metasurfaces such as these therefore show good prospects as tunable narrow band filters.

The frequency selective metasurface used in our experiment consists of a square lattice of asymmetric silicon resonators on a quartz substrate (see inset in Fig. 1a,b). When the metasurface is infiltrated with LCs, the resonance condition of the meta-atoms becomes dependent on the refractive index of the LC medium. Importantly, the LC refractive index can be easily adjusted through either heating or the application of an electric field due to the LCs temperature and electric field dependent anisotropic refractive index [3]. We fabricated the LC cell using the metasurface as the base substrate and covered it with a layer of positive dielectric anisotropic LC molecules (E7 LC mixture). The thickness of the cell was set by 5 μm spherical plastic spacer particles blown onto the metasurface prior to infiltration with E7. To achieve initial orientation of the LCs, an alignment layer of nylon6 was spin-coated on the upper substrate and rubbed in the x-axis direction. The light was incident from the back of the cell to ensure that the polarization was not affected by the birefringence of the LCs in their nematic state.

We also performed computational studies in Lumerical of the tunability of the resonance with a change in the LC refractive index (including the change from the nematic to isotropic phase) due to heating. To obtain simulation results that are a function of temperature we used the known temperature dependence of n_o and n_e of E7 LC [4], where n_e is parallel to the director of the LCs. Our simulations predict that the resonance will be blue shifted as the medium's temperature increases, as shown in Fig. 1(a). It should be noted that the simulations assume a perfect alignment of the LCs, while in reality there will be some deviation as the LCs will only partially align to the surfaces of the Si nano-resonators. Nevertheless, the main features of the simulated response are reproduced in the experiment.

Fig. 1(b) shows the experimental results for the temperature dependence of the transmittance spectra. The heating of the cell was stabilized using a PID control loop on a temperature controller. Because both the n_o and n_e refractive indices of the LCs depend on temperature, we observe a spectral tuning of the resonances due to the heating of the

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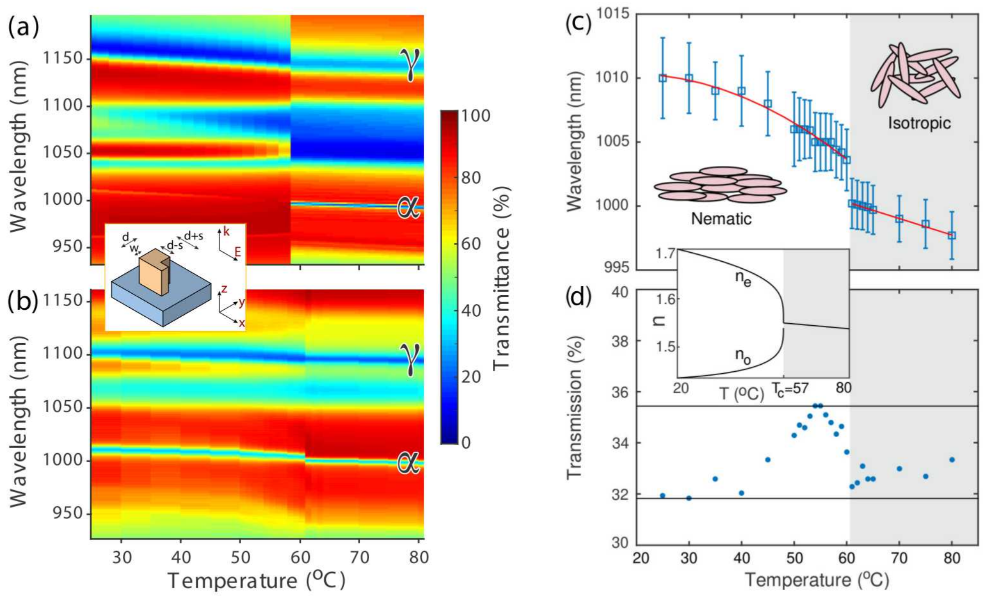

Fig. 1. (a) Simulation of the temperature dependence of the transmittance spectrum done in Lumerical. The studied resonance is marked α, while a prominent Fano is marked γ. (b) Experimentally measured transmittance spectra. The inset shows the meta-atom geometry. (c) The shift of the resonance with temperature, where the vertical bars mark the FWHM. The red line is the best fit with a second order polynomial in the nematic state and a linear fit in the isotropic state. (d) The minimum transmission of the resonance as a function of temperature. The inset shows the temperature dependence of the refractive index of E7 liquid crystals at $\lambda = 1550$nm.

LC. The experimental results show that the resonance has a constant contrast (maximum to minimum transmission) of approximately 55 percentage points, which does not dramatically change with temperature. The measured quality factor of the resonance is $\lambda_0/\Delta\lambda = 270 \pm 30$ in the isotropic LC state, where λ_0 is the resonance wavelength. The figure of merit for the tuning of this resonance is 3.3 ± 0.6. The discontinuity in the graph is due to the phase transition of the LC from the nematic to isotropic state. The difference between the measured critical temperature of $\sim 61°$C and the listed value of 57°C for E7 LC is due to temperature gradients across the sample.

The tuning of the resonance is visualized in Fig. 1(c), which shows the resonance wavelength and FWHM as a function of temperature. As can be seen, the shift in the resonance matches the form of the temperature dependence of the refractive index of E7 (Fig. 1 inset) and thus the shift is due to changes in refractive index of the LCs. As can be seen in Fig. 1(d) the minimum transmission of the resonance changes by less than 4% across the temperature range measured, thus showing that the resonance is a good candidate for a band-stop filter across the entire range studied. Because the minimum transmission is 32%, further studies need to be conducted into the resonator design in order to achieve lower transmission in the rejection band.

In conclusion, we have demonstrated the LC tuning of high-Q resonant metasurfaces composed of silicon nanoresonators. By introducing asymmetry into the resonator design, we are able to obtain high quality factor transmission features. Specifically, a narrow band transmission dip of only 3.7 ± 0.3 nm width has been shown to be tunable with a figure of merit of 3.3 ± 0.6. Our results represent the first proof of concept of tuning of narrow band resonances in dielectric metasurfaces, offering a feasible path to the construction of tunable blocking filters which are lightweight & compact and suitable for various applications, including hyper spectral imaging. Importantly, the high-Q resonant metasurfaces offer an unique platform for *nonlinear frequency conversion of high efficiency*. Our platform can thus be extended to the studies of various nonlinear processes, including sum- and difference-frequency generation.

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