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Supplementary information

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Ultra-high extinction-ratio light modulation by electrically tunable metasurface using dual epsilon-near-zero resonances

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Figure S1 shows the impact of the bias connection width on the reflection spectra of the modulator metasurface. The simulations are done in two different bias voltages of $V = 0$ V, and $V = -2.5$ V and three different polarizations of light as $\theta = 0°$, 30° and 45°. As could be seen for $W < 10$ nm the bias lines do not affect the reflection spectra, while for 10 nm < $W \leq 30$ nm has a negligible effect. However, for $W > 30$ nm the reflection spectra start to change, which is caused by moving the resonance inside the accumulation layer of bias lines. Hence, in our design in the manuscript, the width of bias lines is assumed to be 20 nm. Moreover, it is visible that the polarization of the incident light polarization does not affect the performance of the metasurface.

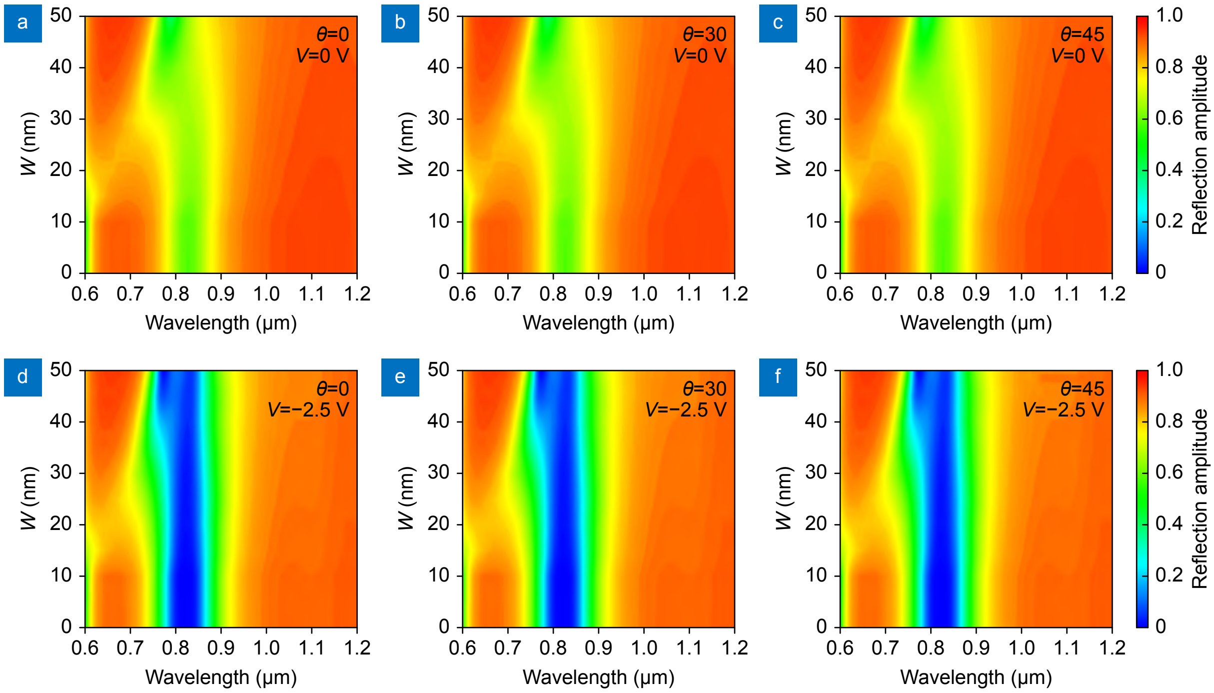

Fig. S1 | Impact of the bias connection on the reflection spectra under *V*=0 V and *V*=−2.5 V. Map of the reflection spectra of the modulator metasurface with a varying width of the bias connection and different polarization angle of the incident light.

Figure S2 shows the impact of the light source incident angle on the reflection spectra of the modulator metasurface. The simulations are done under two different bias voltages of $V = 0$ V, and $V = -2.5$ V as the angle of the incident light is changed from 0° to 45°. As could be seen for the angles smaller than 20° the effect is negligible. Under $V = -2.5$ V, the reflection amplitude at λ = 820 nm gradually increase from 3.58×10^{-3}% to 1.65% as the incident light's angle of increasing from 0° to 45°. Under $V = 0$ V, the reflection amplitude at λ = 820 nm gradually decreases from 56.3% to 39.11% as the incident light's angle increasing from 0° to 45°. As a result, the modulation depth drops to 27 dB from 84 dB as the incident light's angle increasing from 0° to 45°.

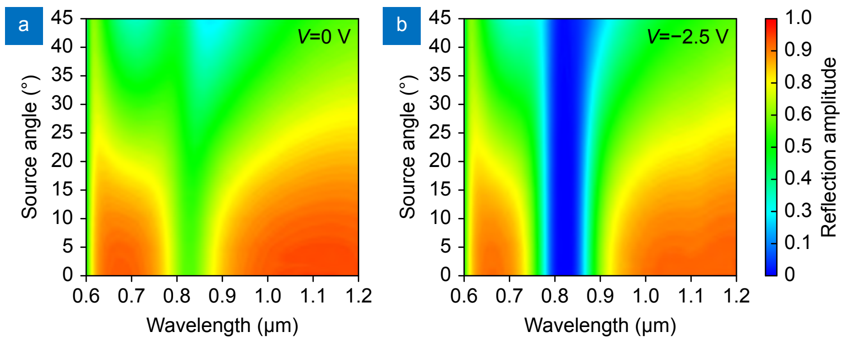

Fig. S2 | Impact of the light source incident angle on the reflection spectra under *V*=0 V and *V*=−2.5 V. Map of the reflection spectra of the modulator metasurface with a varying angle of the incident light.

Figure S3 shows the impact of the ITO discs thickness on the reflection spectra under the bias voltages of $V = 0$ V and $V = -2.5$ V. As shown in Figure S3, under the bias voltage of $V = 0$ V, the resonance wavelength of the magnetic dipole is decreasing from 820 nm to 720 nm as the thickness of ITO discs is increased from 5 to 30 nm. Under the bias voltage of $V = -2.5$ V, the amplitude of the dip is increasing as the thickness of the ITO discs are increasing, while the resonance wavelength is blue-shifting. This implies that the highest modulation depth is achieved for the thinnest ITO thickness of 5 nm.

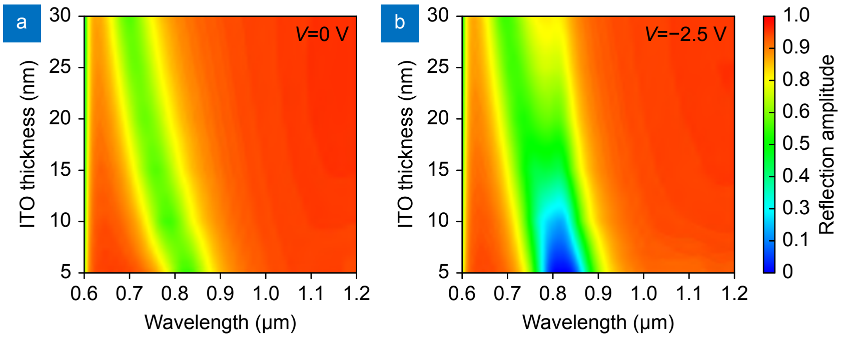

Fig. S3 | Impact of the ITO discs thickness on the reflection spectra. Map of the reflection spectra of the modulator metasurface with a varying thickness of the ITO discs (5 nm ≤ t_{ITO} ≤ 30 nm) under the bias voltages of (**a**) V=0 V and (**b**) V=−2.5 V.