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• Supplementary File •

Tunable lithium niobate metasurfaces for phase-only modulation based on quasi-bound states in the continuum

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Appendix A Multipole decomposition

To shed light on the multipole contribution of the two QBICs, we have examined the magnetic and electric multipoles using the Cartesian multipole decomposition method. The multipole expansion of the electric dipole (ED) moment, magnetic dipole (MD) moment, electric quadrupole (EQ) moment, magnetic quadrupole (MQ) moment, and toroidal dipole (TD) moment can be written out as [1]:

$$ED = \frac{1}{i\omega}\int J(r)d^3r$$

$$MD = \frac{1}{ic}\int (r \times J(r))d^3r$$

$$EQ_{\alpha\beta} = \frac{1}{2i\omega}\int [r_\alpha J_\beta(r) + r_\beta J_\alpha(r) - \frac{2}{3}(r \cdot J(r))\delta_{\alpha\beta}]d^3r$$

$$MQ_{\alpha\beta} = \frac{1}{3c}\int [(r \times J(r))_\alpha r_\beta + (r \times J(r))_\beta r_\alpha]d^3r$$

$$T = \frac{1}{10c}\int [(r \cdot J(r))r - 2r^2 J(r)]d^3r$$

Here, ω and c are the angular frequency and speed of the light in a vacuum, respectively. The symbols α, and β represent x, y, and z, respectively. The induced electric current density is obtained by:

$$J(r) = -i\omega\epsilon_0[\epsilon_r(r) - 1]E(r)$$

$E(r)$ is the electric field in the Cartesian coordinate system at the internal points r= (x, y, z).

Appendix B C_{2v} symmetric metasurface

Among the various metasurface designs, the C_{2v} symmetric metasurface consisting of four elliptical cylinders has garnered significant attention for its ability to support dual quasi-BIC modes simultaneously. And the properties of those BIC modes can be controlled by tuning the geometric parameters. The combination of BIC and Huygens' regime within this C_{2v} symmetric metasurface (dubbed as extreme Huygens' metasurface) offers possibilities to optimize the performance of the tunable Huygens' metasurface. To demonstrate the symmetry of those two QBICs, the y-component electric field of the E-QBIC and M-QBIC is plotted and presented in Fig. B1(a) and B1(b). The E-QBIC mode exhibits a symmetric profile along the vertical direction with an anti-node formed at the center, indicating the even mode parity symmetry of the E-QBIC. The M-QBIC has an anti-symmetric field distribution along the vertical direction with a node formed in the center. These characters show the odd mode parity symmetry of the M-QBIC [2,3].

The z-component of electric field profiles E_z of two modes are demonstrated in Fig. B1(c). The $LiNbO_3$ metasurface possesses a C_{2v} symmetry at θ=0°. Moreover, the structure maintains the C_{2v} symmetry during the θ increases. When the rotation perturbation θ is introduced, the slight distortion of E_z triggers the transformation of BIC into QBICs, enabling the mode coupling to the far field [4].

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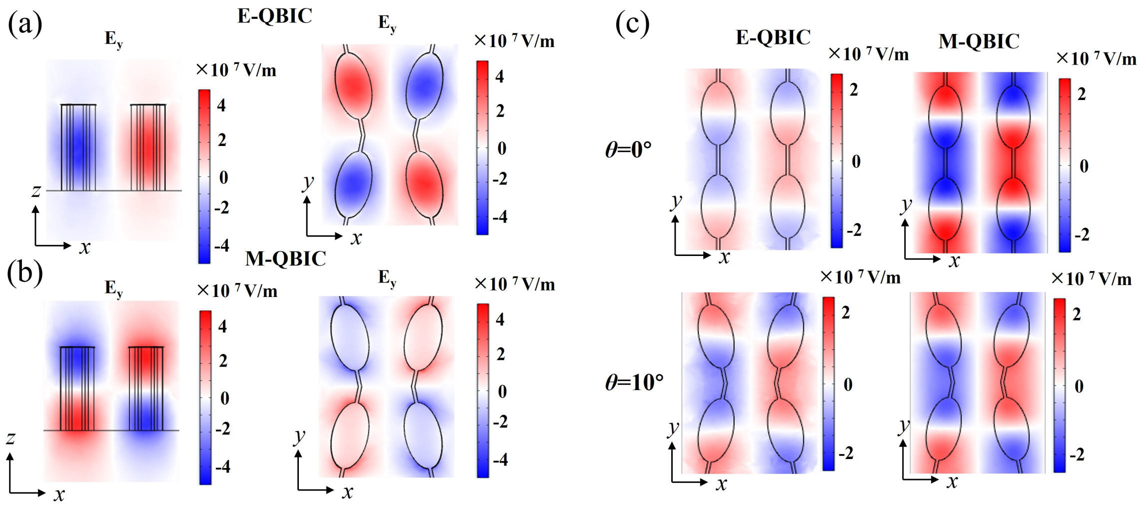

Figure B1 The y-component of E-QBIC (a) and M-QBIC (b) electric field profiles, respectively. (c)The z-component of electric field profiles of E-QBIC and M-QBIC, respectively.

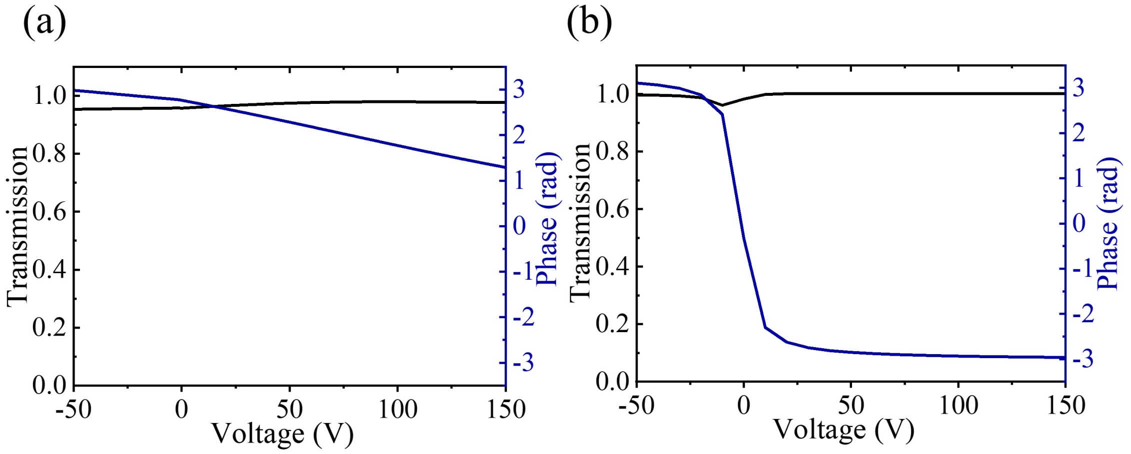

Figure C1 The transmission and phase spectra as functions of the applied voltage at Q=200 (a) and Q=3500 (b).

Appendix C Electrical modulation characteristic

As the z-cut $LiNbO_3$ is used, $LiNbO_3$ possesses EO coefficients of γ_{33}=30.9 pm/V in the extraordinary axis. The variation of the $LiNbO_3$ refractive index with external voltage can be described as [5]:

$$n = n_e + 0.5 n_e^3 \gamma_{33} E$$

Here, n_e=2.14 is the extraordinary refractive index for the zero applied electric field. $E = V/h$, where V is the applied voltage and h is the thickness of the $LiNbO_3$. Because the voltage is applied along the z-axis, the change of the ordinary refractive index with the applied voltage can be neglected [6].

The $LiNbO_3$ metasurface is operated at the Huygens' regime, where the Huygens' mode is detuned via electro-refraction induced in the $LiNbO_3$. We have compared the amplitude and phase for $LiNbO_3$ metasurfaces with different Q factors. The transmission property shown in Fig. C1(a) is calculated at operating wavelength 1481nm. When the Q factor is 200, the 2π phase modulation fails with the voltage increase from -50V to 150V. The Q factor of the $LiNbO_3$ metasurface shown in Fig. C1(b) is 3500 at operating wavelength 1463nm. By contrast, a nearly 2π phase modulation and near-unity transmission amplitude are obtained with the applied bias increases from -50V to 150V. Notably, the modulation strength of voltage to the phase can be optimized by improving the Q factor. A larger Q factor means a longer lifetime of photons, which enhances the localization of the field within the active regions of resonators. Thus, the optical path is elongated, and the tunability resultant from the electro-refraction is boosted. These slight variations in the transmission amplitude are attributed to the loss of transmitted radiation from the reflections that the spectra of the E-QBIC and M-QBIC are not completely overlapping. An ideal Huygens' regime demands spectrally overlapping electric and magnetic resonances of equal strength and width, which is almost impossible to obtain in practice. The $LiNbO_3$ metasurface with a larger Q factor possesses narrower resonance widths. The subtle difference in resonance widths has a greater effect on the transmission amplitude [7]. Therefore, a more obvious amplitude change exists in Fig. C1(b) at Q=3500.

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