Supplementary Information

Microelectromechanical Maltese Cross Metamaterial with Tunable Terahertz Anisotropy

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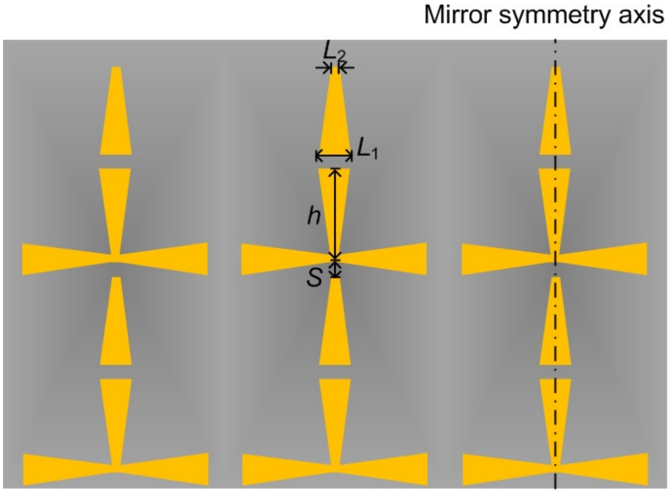
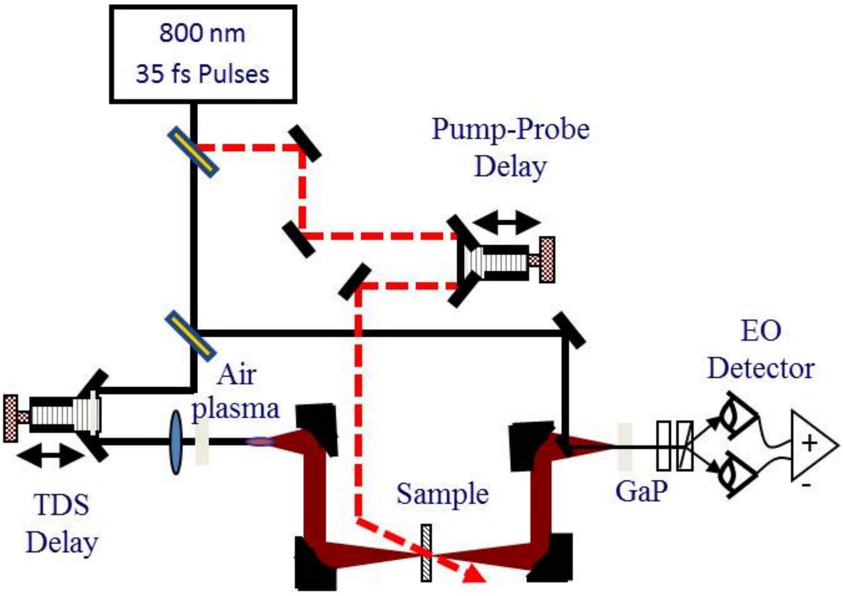
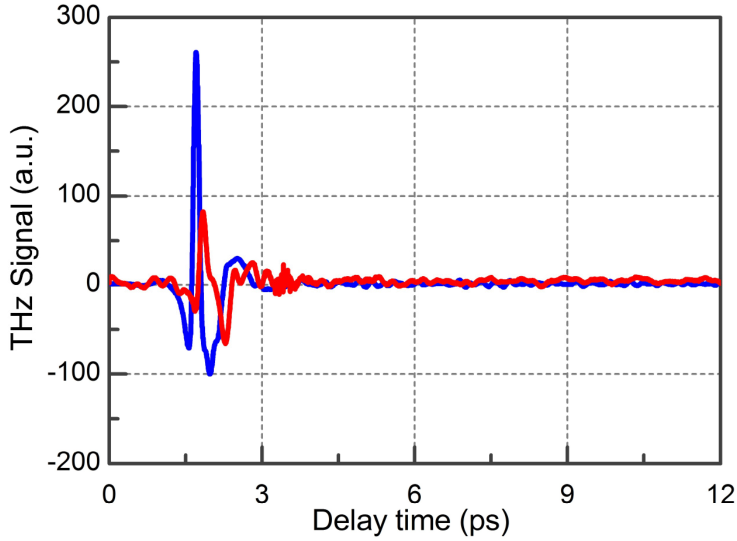


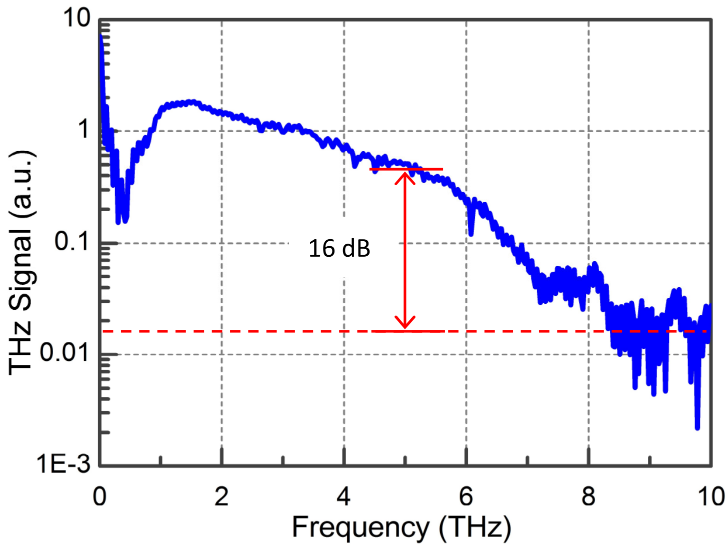
Supplementary Figure S1 | Design parameters for the Maltese cross metamaterials. The cross-shaped unit cell is consisted of four trapezoid metal strips with the height h = 11 μm, the longer parallel side L_1 = 4 μm and the shorter parallel side L_2 = 1 μm (Fig. 1(b~d)). The period of the square lattice is 28 μm. The movable trapezoid can be actuated with the shift distance S ranging from 0 μm to 5 μm.



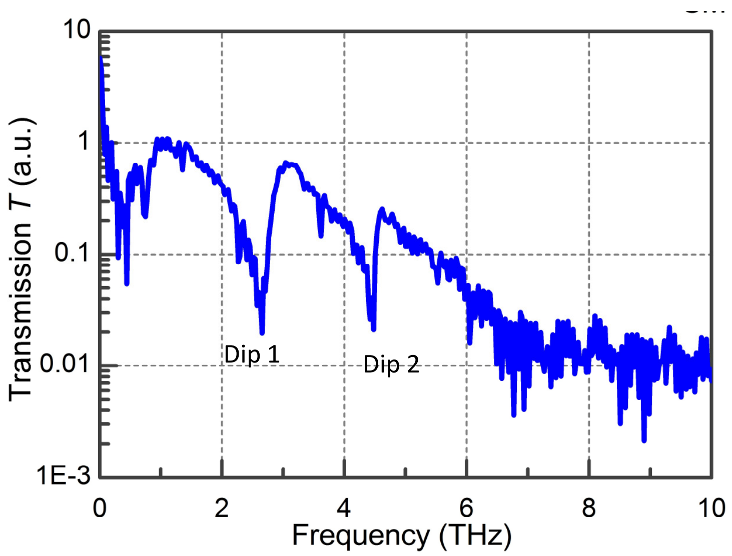
Supplementary Figure S2 | OPTP system for the experimental characterization of the Maltese cross metamaterial. The THz probe pulse is generated by 35-fs pulses at center wavelength of 800 nm with a repetition rate of 1 kHz by using air-plasma technique. The spectrum range of the THz pulse is from 0.3 to 8 THz, which is detected by free-space electro-optical (EO) sampling with a 0.3-mm thick <110> Gallium phosphide (GaP) crystal.



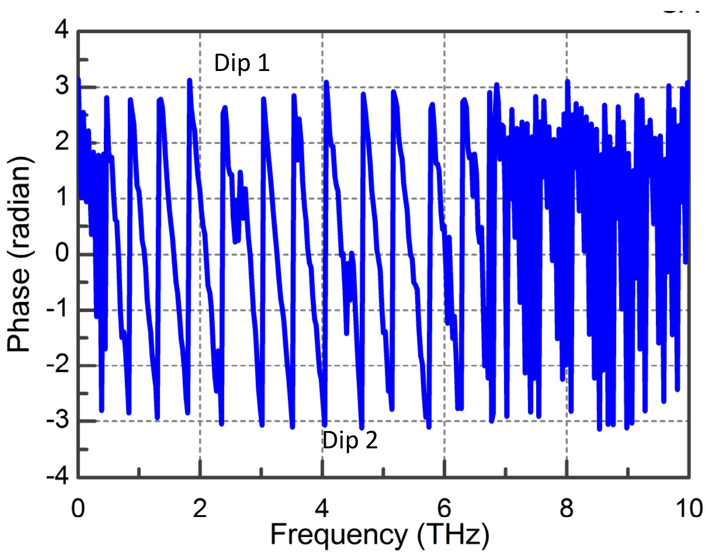
Supplementary Figure S3 | Time-domain THz waveforms for the source and the Maltese cross metamaterial. The blue and red lines show the waveform of the source and the THz pulse passed through the metamaterial when $S = 2.5$ μm, respectively.



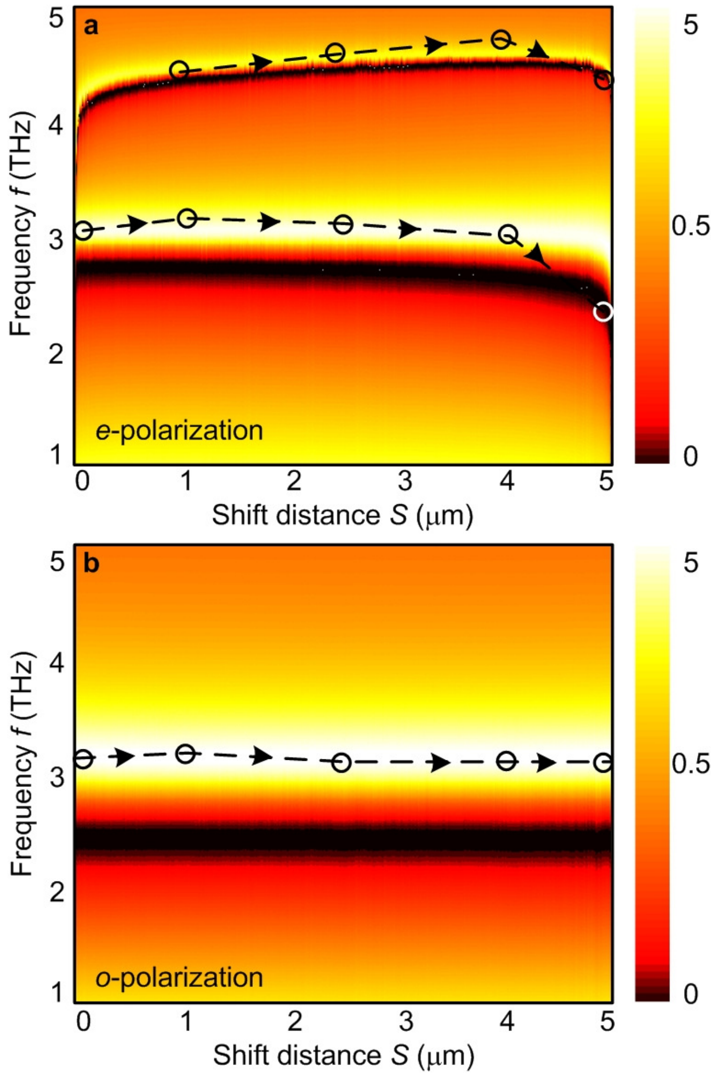
Supplementary Figure S4 | Spectral amplitude of the source derived by using Fourier transform methods. The spectrum range is from 0.3 to 8 THz. The signal noise ratio is measured to be approximately 16 dB at 5 THz.



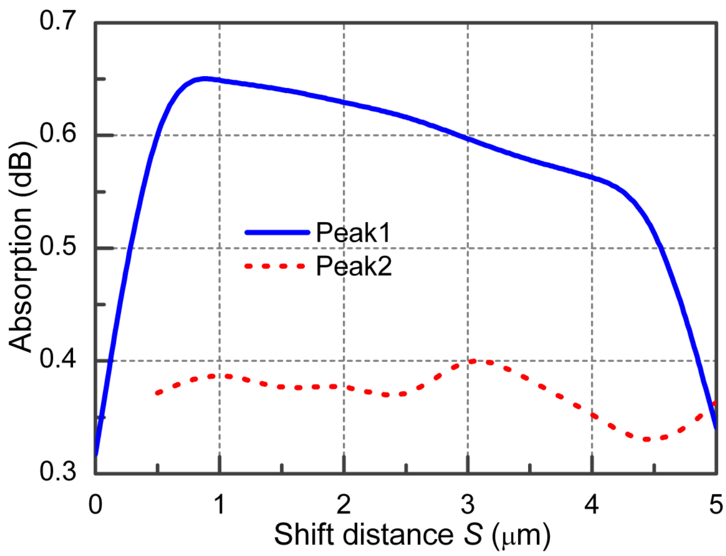
Supplementary Figure S5 | Spectral amplitude of the Maltese cross metamaterial when *S* = 2.5 μm. The two transmission dips, which can map to the two resonance dips as shown in Fig. 3c, can be clearly observed in the amplitude spectrum derived by using the Fourier transform of the time-domain THz waveforms.



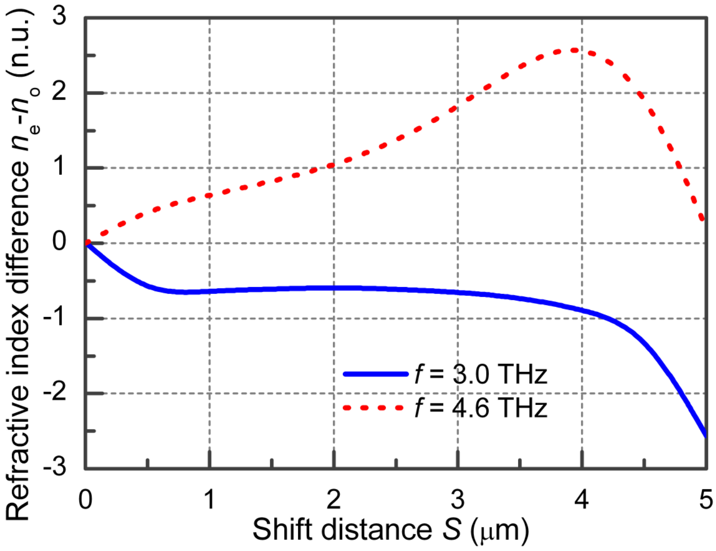
Supplementary Figure S6 | Phase spectrum of the Maltese cross metamaterial when *S* = 2.5 μm. The phase shifts of at the resonance dips are marked as Dip 1 and Dip 2, respectively. The spectra derived by using Fourier transform method are normalized with the source. In Fig. 3, twenty equally spaced data points with the least-mean-square-error is chosen as compared with the simulation results.



Supplementary Figure S7 | Contour map of transmission as the function of incidence frequency *f* and shift distance *S*. The bright region shows the high transmission region while the dark region shows the transmission dip. The transmission peak frequency at low and high frequency region has monotonous red and blue shift, respectively as the S is increasing, when the movable beam is not connected with the fixed part (0 μm < *S* < 5 μm). The measured resonance peaks are marked by circles, which show a good agreement with the simulation results.



Supplementary Figure S8| Numerical analysis of the ohmic absorptions of the transmission peaks under different shift distances *S*. The transmission peaks in high frequency region (Peak2) have lower ohmic absorption than that of the peaks in low frequency region (Peak1), which is due to the fast decaying of the absorption profile at high frequency region.



Supplementary Figure S9 | The differences between the effective refractive indices of *o*- and *e*-polarized incidence, which shows the optical anisotropy of the Maltese cross metamaterials. There is an abrupt change of the optical anisotropy at both low and high frequency regions, when the movable beam is disconnected to the fix parts. The shift of the moveable beam has larger effects on the optical anisotropy of the high frequency region (4.6 THz) than that of the low frequency region (3.0 THz). This real-time tuning process is verified by the calculated effective permeability of the metamaterial, which is derived from the measured reflection spectra using the Fresnel fit [38]. More specifically, the transmission coefficient T of the Maltese cross structure can be expressed as the function of the effective permittivity and permeability of the tunable metamaterial $T = T(\mu_{\text{eff}}, \mu_{\text{eff}})$ (see Eq. (4) of Ref. [38]). The measured reflection spectrum is fitted using

$$\varepsilon(\omega) = \varepsilon_s - \frac{A_e \omega_p^{\ 2}}{\omega^2 - \omega_{e0}^2 + i\omega r_e}, \tag{S1}$$

$$\mu(\omega) = 1 - \frac{A_m \omega^2}{\omega^2 - \omega_{m0}^2 + i\omega r_m}, \quad \text{(S2)}$$

here $\varepsilon(\omega)$ and $\mu(\omega)$ are effective permittivity and permeability, respectively. ω is incident frequency, ω_{m0}, ω_{e0}, A_e, A_m, r_e, r_m, *and* ε_s are fitting factors. The Fresnel fitting method is first examined by fitting the Transmission spectra for both *e*- and *o*-polarized incidence. The fitting factors chosen by least-squares minimization are submitted to Eq. (S1) and Eq. (S2). Then the effective refractive index is obtained by $n_{eff}(\omega) = \sqrt{\mu(\omega)\varepsilon(\omega)}$