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ABSTRACT

Active polarization switching devices are important to control the polarization state of light including terahertz (THz) waves that are technologically challenging to manipulate. Here, we propose and numerically demonstrate a hyperbolic metamaterial-based (HMM-based) active Brewster polarization switch for the intensity and phase modulation of THz light. The proposed multilayered HMM consists of alternating thin layers of high temperature superconductors such as yttrium barium copper oxide and dielectric materials such as lanthanum aluminate. The HMM shows elliptical dispersion above the superconducting phase transition temperature and type II hyperbolic dispersion in the superconducting state. By varying the temperature from the dielectric to the superconducting phase of the HMM, we demonstrate above 98% THz intensity modulation and 100% phase tunability (180°) at Brewster's angle. The proposed HMM can work as an efficient reflective THz modulator by properly selecting the angle of incidence.

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I. INTRODUCTION

Terahertz modulators are one of the important components in the terahertz (THz) technology that can find applications in communications, spectroscopy, and imaging.^{1–3} Various solid-state and non-solid-state THz modulators with both broad and narrow bandwidth responses were demonstrated by integrating the photonic structures with tunable conductive materials such as semiconductors, superconductors, perovskites, 2D materials (graphene, MoS₂, etc.), phase change materials, and liquid crystals.^{4–10} We note that most of the narrow bandwidth THz modulators rely on narrowband resonance effects such as using metamaterials and plasmonic systems, which require intense lithography steps.^{9–12} Since a broad bandwidth operation is important for many applications, it can be achieved with non-resonant graphene-based solid-state devices.^{13–15}

However, it is challenging to develop THz modulators with high modulation depth (MD), broad operation bandwidth, and high modulation speed. In particular, the active control of THz modulators with high intensity and phase tunability is essential for various applications. On the other hand, active control of the polarization state of light in different spectral bands can find a plethora of applications in optics. Two conditions must be satisfied to realize effective reflective type active polarization switches:¹⁶ (i) *s*-polarized reflected intensity should be unity with and without external stimulus and (ii) the absolute modulation depth of *p*-polarized reflected intensity at the resonance should be close to 100%. In particular, the second condition essentially allows active switching. However, it is a challenging task to realize 100% modulation depth in most of the spectral bands.

Over the past few years, hyperbolic metamaterials (HMMs) have attracted significant attention due to their extreme anisotropic permittivity and ease of fabrication using conventional thin film physical vapor deposition techniques, by depositing thin metal-dielectric multilayers in the effective medium regime.¹⁷ Several applications of HMMs in a wide spectral band from ultraviolet to terahertz have been demonstrated by combining different metals and dielectrics.^{18–23} Various material combinations have been used to engineer the dispersion relation of HMMs in different spectral bands. At THz frequencies, tunable HMMs are realized with graphene and topological insulators.^{24–28} It has been shown that high Tc superconductors (HTSs) exhibit hyperbolic dispersion in the far infrared and THz frequencies since superconductivity in most HTS materials could be achieved above liquid nitrogen temperature.²⁹ More importantly, the superconductor-based HMM increases the superconducting critical temperature, which may be considered a metamaterial route to high temperature superconductivity.^{29–31}

In this work, we propose and numerically demonstrate a terahertz modulator or an active polarization switch using a high Tc

superconductor-based HMM. By exciting the Brewster mode of the HMM and varying the external stimulus as temperature, we realize above 98% intensity modulation and 100% phase tunability. The observed intensity and phase tunability are better compared to existing non-resonant solid-state devices.

II. RESULTS AND DISCUSSION

The proposed HMM-based THz modulator is depicted in Fig. 1(a), which consists of alternating thin layers of high Tc superconductors such as yttrium barium copper oxide (YBCO) and dielectric materials such as lanthanum aluminate (LAO). YBCO is the widely used high Tc superconductor with transition temperature above liquid nitrogen temperature. We selected LAO as the dielectric because it is the suitable dielectric material for the lattice matched deposition of YBCO thin films. The total thickness of HMM is set to $1.6\mu\text{m}$. The complex uniaxial permittivities of HMM can be obtained using the effective medium theory (EMT). Since we assume both layers to be non-magnetic ($\mu = 1$), the

FIG. 1. (a) Principle of the Brewster's angle effect in type II YBCO–LAO HMM. An unpolarized light incident on the HMM splits into s- and p-polarizations. The reflected and refracted light are s- and p-polarized, respectively. EMT derived permittivity components for different temperatures. (b) Real parts of parallel and perpendicular permittivity components. (c) Imaginary parts of parallel and perpendicular permittivity components.

parallel and perpendicular uniaxial permittivity components of YBCO-LAO HMM are given by¹⁸

$$\varepsilon_{||} = f_m \varepsilon_m + f_d \varepsilon_d, \quad (1)$$

$$\varepsilon_{\perp} = \frac{\varepsilon_m \varepsilon_d}{f_m \varepsilon_m + f_d \varepsilon_d}, \quad (2)$$

where (ε_m, f_m) and (ε_d, f_d) are the complex permittivity and fill fraction of YBCO and LAO, respectively. Experimentally determined permittivities of YBCO and LAO are used in EMT calculations. For the considered THz frequency band (0.3–1.1 THz), LAO permittivity is almost constant even with the temperature change, which is ~ 25 (see Fig. S1 in the [supplementary material](#)). However, the permittivity of YBCO significantly changes with frequency and temperature. We determined the complex permittivities of the 25 nm thin YBCO thin film using THz spectroscopy and used them in the calculations (see Fig. S2 in the [supplementary material](#)). The fill fractions of both YBCO and LAO are set to 50%.

In Fig. 1(b), we show the calculated real parts of parallel and perpendicular permittivity components for different temperatures. Corresponding imaginary parts of the permittivity components are shown in Fig. 1(c). Since the superconducting transition temperature of YBCO is 80–93 K, we varied the temperature from 100 K to 20 K. As can be seen, real and imaginary permittivities of both components are positive above the transition temperature (100 K). However, real $(\varepsilon_{||})$ shows negative permittivity when the temperature is lowered below the transition temperature of YBCO. It indicates that YBCO-LAO HMM is a dielectric material (elliptical dispersion) above the superconducting transition temperature of YBCO, and it shows type II hyperbolic dispersion in the superconducting phase of YBCO. In particular, the type II hyperbolic dispersion bandwidth increases with decreasing temperature. This is because the frequency dependent conductivity of YBCO increases with decreasing temperature in the superconducting phase.

It has been shown that type I HMMs support the Brewster mode since the real $(\varepsilon_{||})$ components are positive.³² However, type II HMMs do not support the Brewster mode due to negative real $(\varepsilon_{||})$ components. Since the proposed HMM is a type II HMM, it can be used for the intensity and phase modulation of THz light by selecting the incidence angle close to Brewster's angle. The working principle of the proposed THz modulator is based on the optical topological transition of YBCO-LAO HMM from elliptical to type II hyperbolic dispersion. In the dielectric phase of YBCO-LAO HMM, it supports the Brewster mode. In particular, both the intensity and the phase of the THz light can be modulated at Brewster's angle by varying the temperature above and below the superconducting transition temperature.

To numerically demonstrate the performance of the proposed THz modulator, we simulated the angular reflectance spectra for p - and s -polarized light using the transfer matrix method (TMM).³³ The p - and s -polarized reflection coefficient (r_p and r_s) for an N -layer system can be obtained from

$$r_p = \frac{(M_{11} + M_{12}q_N)q_1 - (M_{21} + M_{22}q_N)}{(M_{11} + M_{12}q_N)q_1 + (M_{21} + M_{22}q_N)}, \quad (3)$$

$$M = \prod_{k=2}^{N-1} M_k = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix}, \quad (4)$$

with

$$M_k = \begin{bmatrix} \cos \beta_k & -i \sin \beta_k / q_k \\ -iq_k \sin \beta_k & \cos \beta_k \end{bmatrix}, \quad (5)$$

where

$$\beta_k = d_k \left(\frac{2\pi}{\lambda} \right) (\varepsilon_k - n_1^2 \sin^2 \theta_1)^{1/2}. \quad (6)$$

For p -polarization,

$$q_k = \left(\frac{\mu_k}{\varepsilon_k} \right)^{1/2} \cos \theta_k = \frac{(\varepsilon_k - n_1^2 \sin^2 \theta_1)^{1/2}}{\varepsilon_k}. \quad (7)$$

For s -polarization,

$$q_k = \left(\frac{\varepsilon_k}{\mu_k} \right)^{1/2} \cos \theta_k = (\varepsilon_k - n_1^2 \sin^2 \theta_1)^{1/2}. \quad (8)$$

Here, λ is the wavelength of the incident light, θ_1 is the angle of incidence, and ε_k and d_k represent the dielectric constant and thickness of the k th layer, respectively.

The phase difference between p - and s -polarization is obtained as $\phi_d = |\phi_p - \phi_s|$, where

$$\phi_{p,s} = \arg(r_{p,s}). \quad (9)$$

In our TMM calculations, we simulated the angular reflection spectra for p - and s -polarization by considering HMM as a multilayer of YBCO and LAO thin films and using a single layer effective medium approach. In addition, we simulated the reflection spectra using COMSOL simulation software. We note that the results obtained using three approaches are comparatively similar (see Fig. S3 in the [supplementary material](#)). In the following discussion, we present the results obtained by TMM where we consider HMM as a multilayer of YBCO and LAO thin films.

Figure 2 shows the 2D map of the angular reflectance spectra for two temperatures, one above (100 K) and one below (20 K) the transition temperature. It is evident that HMM supports Brewster's angle (86°) at 0.98 THz in the dielectric phase of HMM (100 K), where the p -polarized reflected intensity is almost zero [Fig. 2(a)] and the s -polarized reflected intensity is 100% [Fig. 2(b)]. However, the p -polarized reflected intensity is increased to 77% [Fig. 2(c)], while keeping 100% s -polarized reflected intensity [Fig. 2(d)] when the temperature is reduced to 20 K. We found that the s -polarized reflected intensity remains 100% for all temperatures, and the reflected intensity of p -polarized light can be tuned from zero to a maximum value at Brewster's angle by varying the temperature from 100 K to 20 K. The modulation depth (MD) of p -polarized

FIG. 2. Simulated angular reflectance spectra for (a) *p*-polarization at 100 K, (b) *s*-polarization at 100 K, (c) *p*-polarization at 20 K, and (d) *s*-polarization at 20 K.

reflected intensity can be obtained from¹⁵

$$D = \left(1 - \frac{|r|^2}{|r_{\max}|^2} \right) \times 100\%, \quad (10)$$

where r is the minimum reflectance at the off-state and $r_{\max}$ is the maximum reflectance at the on-state. Figure 3(a) shows the active tuning of the *p*-polarized reflected intensity at Brewster's angle (86°) by varying the temperature. As can be seen, close to zero reflectance is obtained for 100 K at 0.98 THz, and the reflected intensity increased with the decreasing temperature. Also, note that the reflected intensity saturates at lower temperatures due to the saturation behavior of permittivity components of HMM. By considering off-state reflectance at 100 K and on-state reflection at 20 K, the calculated modulation depth of the *p*-polarized reflected intensity at 0.98 THz is over 98%. It shows that YBCO-LAO HMM fulfills the two conditions required to realize efficient reflective type

active polarization switches.¹⁶ In particular, YBCO-LAO HMM shows the active control of the polarization state of light by operating around Brewster's angle.

It is known that the reflection phase undergoes $\sim \pi$ phase shift at Brewster's angle.³⁴ In Fig. 3(b), we show the simulated reflected phase difference between *p*- and *s*-polarized light for different temperatures at 86°. As expected, around 180° phase shift is obtained when the HMM is in the dielectric phase (100 K). However, the phase shift reduced to 0° when the temperature is decreased to 70 K due to the type II conducting phase of HMM. It shows that 100% tunability in the reflection phase is possible when the temperature is slightly tuned below the transition temperature. In addition, the calculated insertion loss ($\log_{10}|r_{\max}|^2$) of the HMM-based modulator is approximately -2.3 dB. Notably, the realized phase tunability and insertion loss are much better compared to a graphene-controlled Brewster's angle device-based THz modulator.¹⁵

We further simulated the reflectance spectrum of a 200 nm thick YBCO film to prove that a thin film of YBCO alone does not

FIG. 3. (a) Simulated *p*-polarized reflectance spectrum at 86° for different temperatures. (b) Simulated phase difference at 86° for different temperatures. Simulated *p*-polarized angular reflectance spectra of the 200 nm thick YBCO film for (c) 100 K and (d) 20 K.

function as a THz modulator. In Figs. 3(c) and 3(d), we show the *p*-polarized angular reflectance spectra of the 200 nm YBCO thin film for 100 K and 20 K, respectively. In the TMM simulation, we used experimentally determined permittivities of the 200 nm thick YBCO film (see Fig. S2 in the [supplementary material](#)). As can be seen, no considerable change in the THz intensity is observed since it does not support Brewster's angle. In short, the observed 98% intensity modulation and 100% phase tunability are solely due to the phase transition of the YBCO-LAO HMM from elliptical (dielectric) to type II hyperbolic dispersion. To further emphasize this, we simulated the electromagnetic field distribution of the air-HMM-air system using the transfer matrix method. For *p*-polarized light at 0.98 THz and 86° incident angle, the simulated magnetic field (H_z) distribution for 100 K and 20 K is shown in Figs. 4(a) and 4(b), respectively. It is evident that the H_z field

transmits through the HMM for 100 K due to zero reflection at Brewster's angle. However, the H_z component is almost zero for 20 K beyond the HMM due to maximum reflection. In addition, we verified this simulation using an effective medium theory (see Fig. S4 in the [supplementary material](#)). The simulated field distribution clearly indicates the disappearance of Brewster's angle when the dispersion of HMM is changed from elliptical (dielectric) to type II hyperbolic. While this system shows the maximum modulation depth at Brewster's angle, above 90% intensity modulation is still possible by selecting an incident angle around Brewster's angle. The proposed multilayered HMM can be fabricated by physical vapor deposition (PVD) of alternating thin films of YBCO and LAO since the lattice matched deposition of YBCO thin films on LAO is possible (Ceramic coating GmbH, Germany). An optical cryostat-equipped fiber laser-based THz time-domain spectroscopy

FIG. 4. Simulated magnetic field (H_z) distribution for p -polarization at 0.98 THz and 86° for (a) 100 K and (b) 20 K.

setup can be used to perform the angular reflection measurements at cryogenic temperatures.^{6,35}

III. CONCLUSIONS

In conclusion, we demonstrated that a superconductor-based HMM can function as an active Brewster switch for the intensity and phase modulation of THz light. By stacking thin films of the high T_c YBCO superconductor and the LAO dielectric and by varying the temperature above and below the superconducting transition temperature of YBCO, we realized an optical topological transition from elliptical to type II hyperbolic dispersion. We used this feature of YBCO–LAO HMM to realize 98% modulation amplitude and 100% phase tunability by operating at Brewster's angle. The proposed active HMM can find applications in developing efficient reflective type non-resonant solid-state THz modulators.

SUPPLEMENTARY MATERIAL

See the [supplementary materials](#) for experimentally obtained optical constants of LAO and YBCO and additional simulation results.

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DATA AVAILABILITY

The data that support the findings of this study are available within the article [and its [supplementary material](#)].

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