Terahertz Brewster polarizing beam splitter on a polymer substrate

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The performance of a terahertz (THz) Brewster polarizing beam splitter on polymer substrate is studied theoretically and experimentally. Simulations by using finite-element method demonstrate that both transmittance/reflectance and their extinction ratios are better than its 45° counterpart in a broad frequency range. Especially, the reflection extinction ratio improves significantly. The results are also verified experimentally with THz time domain spectroscopy (TDS) and backward wave oscillator (BWO) measurement system.

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There has been tremendous advances in the subwave-length-structure (or meta materials) based terahertz devices over the past decade, including physics, engineering, and fabrication[1−3]. Among which, polarizers or polarizing beam splitters can be used in terahertz (THz) imaging, spectral analysis and communication system to improve their signal-to-noise ratio (SNR) effectively[4−6]. Unlike subwavelength–structured metal grating or dielectric grating can be used as visible or infrared polarizing beam splitters[7−9], metal wire-grid polarizer is the most widely used one in THz range, its performance is related to the period of the wire-grid structure and filling factor[10−12]. Decreasing the period of metal wire-grid and/or increasing the filling factor are effective ways to enhance the transmission extinction ratio. For a 45° polarizing beam splitter, the transmittance of transverse magnetic (TM) wave fluctuates because of the Fabry-Perot (F-P) interference, and the reflection extinction ratio of transverse electric (TE) wave becomes very low. In order to eliminate F-P effect and get higher extinction ratio, Brewster polarizing beam splitters were reported. Berry *et al.*[13,14] theoretically and experimentally analyzed the transmission characteristics of the Brewster splitter. However, the reflection performances are rarely reported.

In this letter, the transmission and reflection characteristics for the wire-grid Brewster polarizing beam splitteron polymer substrate are numerically simulated using COMSOL, a finite-element method, and the results are compared with those of a 45° polarizing beam splitter. The results are further experimentally verified with a THz wire-grid polarizer fabricated using laser-induced and chemical non-electrolytic plating on polyimide (PI) substrate.

The schematic of the THz polarizing beam splitter is similar to that in Ref. [13] (Fig. 1), except for the materials of the substrate and metal grating. The beam splitter consists of a sub-wavelength copper grating on a polymer

substrate, such as PI, and its performance is usually determined by parameters, such as wire grid period, filling factor, and metal thickness. The filling factor is defined as the width of the metal line divided by the period. For a Brewster polarizing beam splitter, the Brewster angle $\theta_{\rm B}$ is given as[15]

$$\theta_{\rm B} = \arctan(n_2/n_1), \tag{1}$$

where n_2 and n_1 are the refractive indices of the polymer substrate and air, respectively.

The characteristics of the Brewster and 45° polarizing beam splitters are initially numerically simulated using COMSOL. For the simulation, the wire grid period, fill factor, and thicknesses of the copper and substrate are 20, 0.5, 2.0, and 125 μm, respectively. The refractive index of air is 1.0. The dielectric constant of the substrate is set to 2.9+0.2i and 5.8×10^7S/m for the copper conductivity. Thus, the Brewster angle is ~59°. The simulation results are shown in Fig. 2. In this letter, we define the transmission extinction ratio as $10\log(T_{\rm TM}/T_{\rm TE})$ and reflection extinction ratio as $10\log(R_{\rm TE}/R_{\rm TM})$, where $T_{\rm TM}$ and $T_{\rm TE}$ are the transmittances for the TM- and TE-polarized waves, respectively, and $R_{\rm TM}$ and $R_{\rm TE}$ are the corresponding reflectances. Compared with the 45°
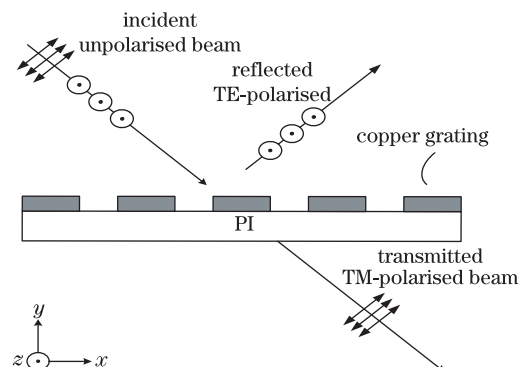

Fig. 1. Schematic of the THz polarizing beam splitter.

polarizing beams plitter, the transmission curve of the TM wave for the Brewster splitter becomes smooth without F-P fluctuations (Fig. 2(a))[10], and its extinction ratio slightly increases. However, the F-P effect still exists for both splitters in the transmission TE mode, resulting in dips and peaks in their extinction ratio curves (Fig. 2(c)). This finding is also true when considering the F-P effect in reflection performances for both splitters (Figs. 2(b) and 2(d)), i.e., the F-P effect exists in both TE and TM modes for the 45° splitter, but only in TE mode for the Brewster splitter. Additionally, the extinction ratio of the 45° polarizing beam splitter is quite low (∼10 dB) in most frequencies, but is quickly enhanced at times to over 25 dB because of the F-P effect. This finding is disadvantageous for practical use. However, the reflection extinction ratio of the Brewster splitter is more than 20 dB in a broad frequency range. Thus, the Brewster polarizing beam splitter is superior to its 45° counterpart in transmittance or reflectance as well as in their extinction ratios.
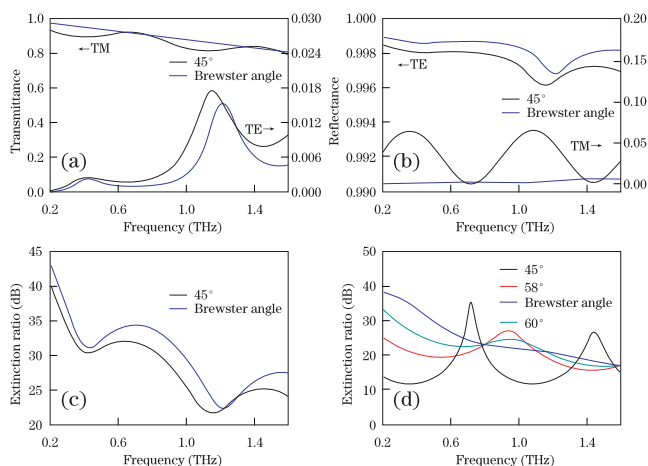

Fig. 2. (Color online) Comparison of the Brewster and 45° polarizing beam splitters. (a) Transmission spectra, (b) reflectance spectra, (c) transmission extinction ratio, and (d) reflection extinction ratio.
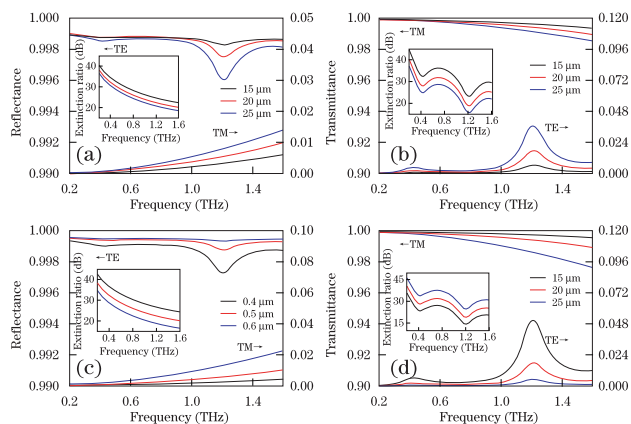

Fig. 3. (Color online) Simulation results of the TE and TM reflectance/transmittance spectra. (a) and (b) Reflectance/transmittance with different periods at fixed filling factor of 0.5; (c) and (d) Reflectance/transmittance with different filling factors at fixed period of 20 μm. The insets show the corresponding extinction ratios.

The influence of period and filling factor on the performance of the wire-grid Brewster polarizing beam splitter is also theoretically analyzed (Fig. 3). As indicated in Figs. 3(a) and (b), the smaller the period of the wire-grid is, the larger the effective TM transmittance and TE reflectance will be. We also obtain higher transmission and reflection extinction ratios. However, the results of the performance with respect to the filling factor are quite different (Figs. 3(c) and (d)). Larger filling factor indicates higher transmission extinction ratio of the splitter, but lower reflection extinction ratio can be obtained simultaneously. Thus, a compromise between the transmission and reflection extinction ratios should be created. The simulations also indicate that the thickness of the metal slightly influences the transmittance and reflectance of the splitter, but enhances the transmission extinction ratio when a larger value is chosen.

A polarizing beam splitter has been fabricated on a 125-μm-thick PI substrate using laser-induced and chemical non-electrolytic plating with copper. The detailed fabrication procedure can be found in Ref. [16]. The wire grid period and filling factor are 20 μm and 0.5, respectively. The thickness of the metal copper is around 2 μm (measured by Dektek150 stylus profiler). The size of the polarizer is 2×2 (cm), which should be sufficiently large because of the large beam spot for the Brewster incident wave.

The broadband transmission of TM/TE waves of the splitter are measured at room temperature using a commercial terahertz time-domain spectroscopy (TDS) with focused beam[17]. To reduce the influence of water vapor and improve the SNR, the light path has been sealed in a box filled with dry nitrogen and less than 1% relative humidity. The experimentally obtained transmission spectra and their extinction ratios for the 45° and Brewster splitters are shown in Fig. 4(a). Brewster splitter are better than those for the 45° splitter over the 0.2 to 1.6 THz range, as predicted by the simulations. Our time domain spectroscopy (TDS) system cannot be used in the reflection mode other than incident 0°. Thus, the reflection characteristics of the fabricated beam splitter are measured using a backward wave oscillator (BWO) system. Given the large collimated THz beam size, the focused optics is also used for the measurement; the divergence of the incident Gaussian beam is ∼6°. The operating frequency ranges from 0.22 to 0.37 THz range for our used backward wave tube (Type OV31, Micro Tech Inc, USA). To improve the degree of polarization of the THz source, a metal wire grid polarizer without substrate (Micro Tech G60×15-S) is inserted in its output. The reflected power of the TM/TE wave by the splitter is measured by a pyroelectric detector and a lock-in amplifier. The results are listed in Table 1. The reflection extinction ratio for the 45° polarizing beam splitter in Table 1 is ∼10 dB, which is in good agreement with simulation (Fig 2(d)). For the Brewster splitter, the reflection extinction ratio is much higher than that of its 45° counterpart; especially, a 14.5-dB improvement is observed at 0.34 THz, but still smaller than that the calculated value. This finding is mainly attributed to the divergence of the focused Gaussian incident beam used in the experiment, whereas the plane-wave condition is assumed in the simulation. The numerical calculations indicate that the reflection
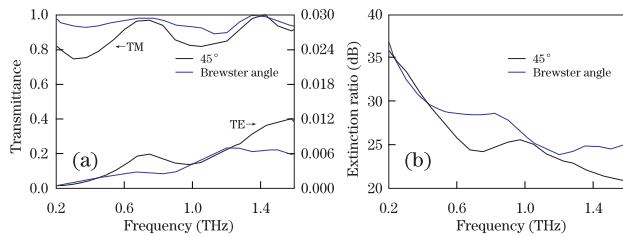
Fig. 4. (Color online) (a) Transmission spectra and (b) the extinction ratios for the 45° and Brewster splitters.

Table 1. Test Results of the Reflection Extinction Ratio

Frequency of BWO (THz)	Reflection Extinction Ratio for 45° Splitter (dB)	Reflection Extinction Ratio for Brewster Splitter (dB)
0.27	12.0	17.0
0.30	11.8	20.4
0.34	8.7	23.2

extinction ratio is very sensitive to the incident angle around Brewster, especially at low frequency (Fig. 2(d)). For example, ±1° deviation will result in up to ∼15 dB decrease in the extinction ratio around 0.30 THz. However, the reflectance of the TE wave does not change around the Brewster angle in the broadband range.

In conclusion, the characteristics of the Brewster polarizing beam splitter on a polymer substrate are numerically simulated using the finite-element method. Both the transmittance/reflectance and their extinction ratios for this splitter are better than those of its 45° counterpart in a broad frequency range. The reflection extinction ratio is improved significantly. A polarizing beam splitter is fabricated on PI substrate using laser-induced and chemical non-electrolytic plating with copper, and measured by THz TDS and BWO-based spectroscopy system. The results are in good agreement with the simulations. To further enhance the transmission and reflection extinction ratios of the splitter, the period of the wire grid of the fabricated device should be reduced, which can be performed using photolithography.

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