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Double Wire-Grid Terahertz Polarizer on Low-Loss Polymer Substrates *

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A double-wire-grid polarizer was fabricated on both sides of a low-loss polythene film by simple electroplating and photolithographic micro-processing techniques. The performances of the polarizer were measured using a terahertz time-domain spectrometer (THz-TDS). The transmittance is more than 70% and below 2% in the parallel and perpendicular directions of the polarizer, respectively. The extinction ratio is better than 22 dB in the broad frequency range of 0.5–3 THz, which is higher than the conventional free-standing polarizer in the high frequency region.

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With the dramatic advances in terahertz (THz) science and technology,[1] many new devices for generation, manipulation, and detection of terahertz radiation have revolutionized the field.[2,3] High quality quasi-optic devices, such as filters,[4] phase modulators,[5,6] and polarizer[7−10] have attracted great interest owing to their potential applications in THz spectroscopy and imaging. The demand for low-loss polarizers is increasing. Free-standing wire-grid-type polarizer behaves as low-loss component as the promising candidate for THz optical devices. However, fabrication of free-standing THz wire-grid devices without substrate is difficult, and the devices often suffer from fragility and imperfection.[11] Wire-grid components made by using the micro-fabrication and nanofabrication on silicon or quartz substrate exhibit Fresnel reflection from planar surface owing to high dielectric constant;[10] nematic liquid crystal polarizers have high extinction ratios in the limited frequency (0.2–1.0 THz) and in the constrained work environment (−10–61°C).[8] Although a single side planar wire-grid polarizer made on the low-loss high density polyethylene substrate with standard photolithographic technology can overcome these shortcomings, whereas it can not avoid the tremendous absorption owing to the thick substrates.[12] Here we present a solid-state planar rectangular-wire-grid polarizer fabricated on both sides of low-loss polythene film substrates by electroplating technology and lithography micro-processing to pattern micrometer-pitch metal wire-grid. The symmetry double wire-grid polarizer has better than 22 dB extinction ratio in the range of 0.5–3 THz, which enables it possible to enhance polarization functions and is expected to open up a new application in THz region.

The sandwiched Cu/polythene/Cu structure has the uniform width of wire approaching to wavelength (100–3000 μm), which makes the polarizer an advantage due to the low-cost of using the simple fabrication process. The cross section of each wire is assumed to be rectangular as shown in Fig. 1(a), where d and a denote the period and wire width of the grid elements, respectively; t and h are the thickness of the polythene core-layer and the depth of the metal grating, respectively. The low-loss polythene film with a refractive index of 1.526 is transparent and almost dispersionless at THz frequency, and reflection from the dielectric surface is negligible. This is the reason why we choose the polythene as the substrate to make the THz optical component. The polarization functions of free-standing wire-grid-type polarizer are governed by the parameters such as the wire width (∼ 10 μm), depth, and period (20–200 μm) of the grid elements.[13]

In the experiments, we selected the ultimate values of diameter and period of frees-standing wire-grid polarizer as the width and period of the double wire-grid polarizer. Cu wire-grids are fabricated on the polythene substrate with uniform period d. The fill factor f was maintained at 0.5, which is defined as the ratio of the width of a single wire to the period of the grating. A copper film with the depth of 15 μm was electroplated on the polythene substrate with the thickness of 40 μm; wire-grid with period of 200 μm was patterned on both sides using photolithographic techniques. The scanning electron microscopy (SEM) image of a fabricated sample is shown in Fig. 1(b).

The transmittance of the polarizer was measured by using a terahertz time-domain spectroscopy (THz-TDS) system in a range of 0.5–3 THz. The THz-TDS

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system is based on linearly polarized photoconductive antennas for both the source and the detector. Samples were mounted on a rotating stage at the focus of the normally incident THz beam (∼ 3 mm in diameter) and were rotated manually, the measurements were performed at room temperature in a dry air atmosphere.

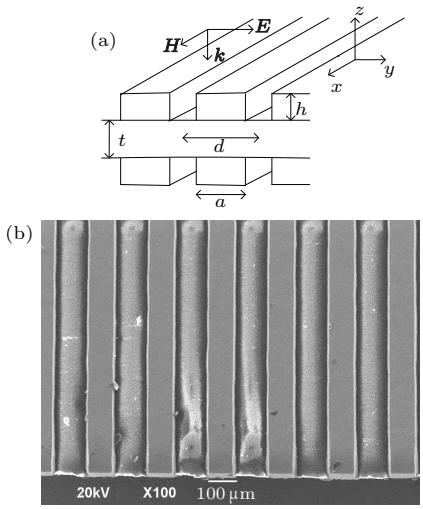


Fig. 1. (a) Schematic of the Double wire-grid polarizer with grating constants $d$and wire width a, the thicknesses of dielectric and metallic film are t and h, respectively. (b) Scanning electron micrograph of polarizer.

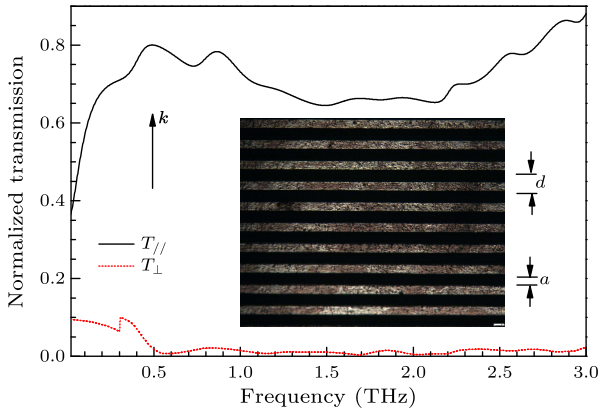


Fig. 2. (a) Experimental transmittance spectra of the polarizer in the perpendicular and parallel direction, denoted with the dotted black line and solid line, respectively. The inset is the optical microscope image.

Figure 2(a) shows the transmission spectra of the polarizer measured by using a THz-TDS system in the range 0.5–3 THz, where $T_{\parallel}$ and $T_{\perp}$ represent the transmittances for the electrical fields parallel and perpendicular to the grating vector direction $\boldsymbol{k}$ at normal incidence, respectively. The inset illustrates the top view of the optical microscope. The polarizer shows very good performances as there are distinguishable transmission properties between $T_{\parallel}$ and $T_{\perp}$, and the transmittances are more than 70% and below 2% in the parallel and perpendicular directions, respectively. The extinction ratio is more than 22 dB in the range 0.5–3 THz, and the maximal extinction ratio exceeds 36 dB at 2.4 THz, which is higher than that of commercial free-standing wire grid polarizer (∼ 25 dB below 1.5 THz).[10] The oscillation with the increasing frequency shows resonant transmission features due to the influences of surface wave.[14] The experimental results confirm that a micrometer-pitch copper wire-grid on both sides with a fill factor of 0.5 is crucial for achieving good transmission in the terahertz region.

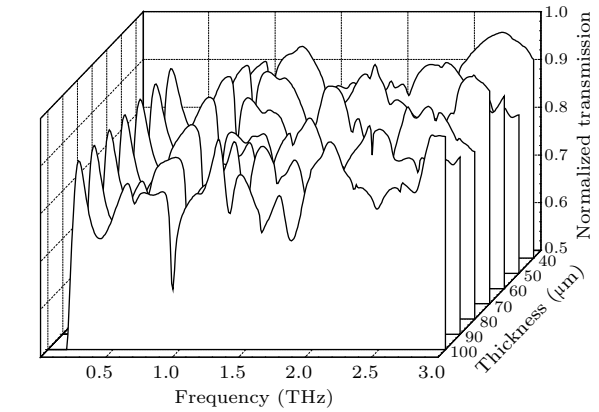


Fig. 3. Simulated transmittance spectra as a function of terahertz frequency and thickness of dielectric core-layer for double wire-grid with uniform period and fill factor.

Computation for the hybrid systems, the metal layers were assumed as semi-infinite in thickness,[14] because at $\lambda_0 = 300\,\mu$m, the field penetration depth in the copper is negligible compared to real thickness. The influence of thickness of the dielectric core layer is simulated according to the rigorous coupled wave analysis.[15] Considering the symmetry structure with finite dielectric core-layer, the wire-grid on both sides can be equivalent to a free-standing metal wire-grid polarizer.[16] The complex refractive index of Cu ($n_m = -5.5 \times 10^5 + i1.2 \times 10^6$) was derived from the Drude model.[17] Electromagnetic plane wave was normally incident upon the surface of the sample. Transmission spectrum is shown in Fig. 3. It is obvious that the peaks of absorption red shift and the amplitudes fall off a little with the increasing core layer thickness, which can be partly contribute to the increase of the absorption with the increasing thickness of the dielectric core layer. In the Cu/polythene/Cu heterostructure, the surface fields in the dielectric attenuate as $e^{-\beta z}$(where β is propagation constant), and exponential decay lengths $|z| = \lambda_0/(2\pi\sqrt{\varepsilon_d})$, ε_d is the relative refractive index of dielectric,[18] λ_0 is the free space wavelength at $\lambda_0 = 300\,\mu$m, $z \approx 32\,\mu$m. When the separation between top and bottom interfaces of metal and dielectric is comparable to or smaller than the decay length of the interface model, interactions between surface plasmon polaritons (SPPs) give rise to coupled modes,[19,20] which will dominate the transmission in-

tensity. Therefore, the transmittance is dominated by the absorption of the substrate and resonance of the localized SPPs along the interfaces of metal and dielectric.

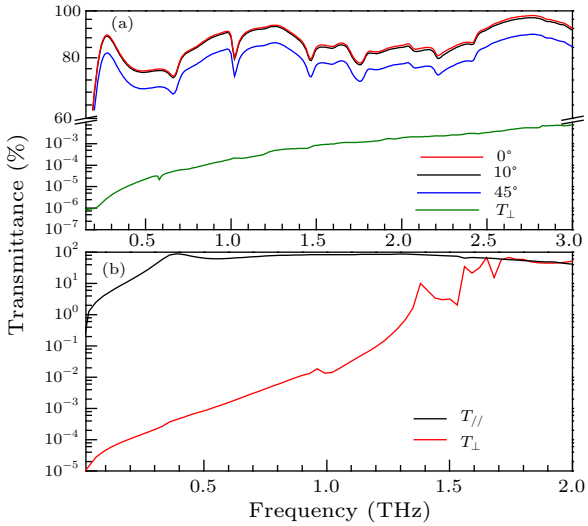


Fig. 4. (a) Simulation transmittance in $T_\parallel$ and $T_\perp$ of double wire-grid polarizer. (b) Simulated results in parallel and perpendicular directions of the single side wire-grid polarizer.

Figure 4(a) shows the simulated transmission in parallel and perpendicular directions as a function of frequencies with a 40-μm-thick dielectric layer. The maximum transmittance in the perpendicular direction is less than 0.01%, the mean extinction ratio is more than 45 dB in the range 0.5–3 THz, and a high value of 76 dB was obtained at 0.25 THz. Moreover, transmission in the parallel direction performs an oscillation growing process with the increasing frequency. The best transmittance is larger than 99% at 2.75 THz. The smallest transmittance is over than 66% at the polarized angle of 45°. However, the extinction ratio of free-standing metal wire grids at 3THz is less than quarter of that at 1THz.[13] It is confirmed that the double wire-grid polarizer has more excellent polarization performances than the free-standing metal wire-grids at high frequencies.

The same dimension single side polarizer is simulated in the 0–2 THz region, transmittance spectra of $T_\parallel$ and $T_\perp$ are shown in Fig. 4(b). The polarizer shows good performance in the low frequency (0–1 THz) range, and the maximal extinction ratio is 53 dB at 0.34 THz. It is worth noting that the operational frequency range of the polarizer is determined by both wire width and the wire spacing. The upper limit of the frequency range for this type of polarizer is approximately 20 times the length of the grating period.[21] Therefore, in the higher frequency range, the performance degrades with the decreasing wavelength. As shown in Fig. 4(b), the transmittance decreases in the parallel and increases in the perpendicular direction. As a consequence, the polarizer has an approximately equivalent transmission coefficient in both the directions at the crucial position (∼ 1.94 THz). With frequency increasing, the transmittance in parallel is less than that in the perpendicular direction. The maximal operating frequency of the single side polarizer is 1.5 THz.

In conclusion, a solid-state planar double-wire-grid THz polarizer fabricated on a low-loss polythene substrate has demonstrated with good performance in the range 0.5–3 THz. The sandwiched Cu/polythene/Cu wire-grid with a fill factor of 0.5, and a period of 200 μm THz polarizer are measured and simulated, and compared with the same dimension single side components. The results show excellent polarization performance of a double wire-grid type polarizer in the broad band frequency range. The fabricated devices make an excellent candidate for use in continuous terahertz wave image systems.

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