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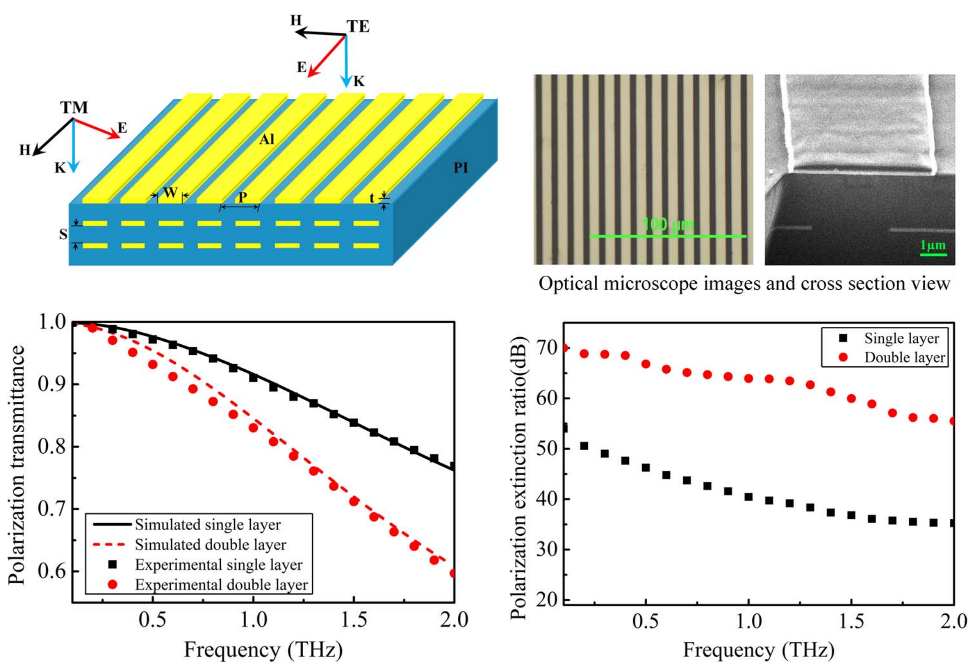

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A Terahertz Polarizer Based on Multilayer Metal Grating Filled in Polyimide Film

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Abstract: Terahertz (THz) polarizers with low reflection and absorption loss and high polarization extinction ratio (PER) based on multilayer metallic gratings filled in a polyimide film were studied theoretically and experimentally. In theory, THz polarization transmittance and PER of single-layer and multilayer polarizers at different THz frequencies were simulated, and their variations with the layer number of the metallic grating structure were discussed. With the increase in the layer number, PER increases prominently due to the evanescent wave coupling between different layers. In the experiment, a double-layer polarizer with an effective diameter of 42.3 mm was fabricated via layered imidization processes and evaluated by the THz time-domain spectroscopy measurements. Results showed that an average transmittance of 80.5% and a maximal PER of 70 dB were achieved, which were in good agreement with the simulated results and were compared with or outperformed most reported single- or double-layer polarizers.

Index Terms: Terahertz (THz), polarizer, subwavelength grating, polarization extinction ratio, low loss.

1. Introduction

Terahertz (THz) radiation is widely used in spectroscopy, imaging and communications [1]–[5], etc. The THz polarizer is a fundamental element to polarize THz radiation or detect the polarization of the THz wave in THz optical systems [6]. The polarization extinction ratio (PER) and the transmission at the polarization direction are the main properties of a polarizer. High-performance THz polarizers are highly demanded for THz sources and detectors and applications in high-sensitive THz spectroscopy detection and THz polarization imaging, etc. [7], but they are often hard to come by.

Metallic sub-wavelength grating is one of widely studied structures for the THz polarizer. To achieve high transmission in the polarization direction, polymer materials such as polyimide

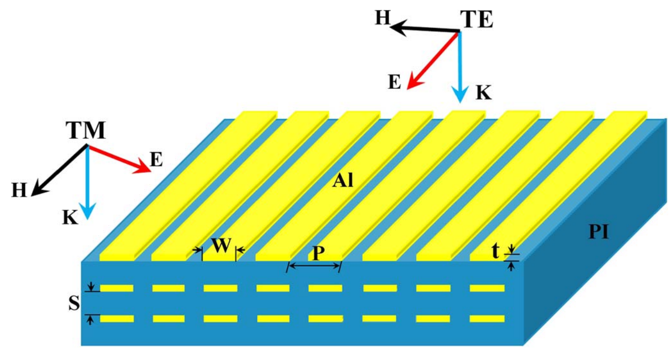

Fig. 1. Schematic diagram of the proposed multilayer THz polarizer.

(PI), polyethylene (PE), and high-density PE (HDPE) with low refractive index and absorption at the THz range are used as the low loss substrate for the THz polarizer. To increase the PER, one common method is to decrease the period of the metallic sub-wavelength grating and change the shape of grating, which will bring difficulties in the structure fabrication. At present, the reported PER of THz polarizers with single- layer metallic grating is about 10 to 50 dB [8]–[12]. To improve it, recently, a terahertz polarizer is presented consisting of a laminated metal-slit array on a polymer film [13]. The copper sub-wavelength grating is fabricated on both sides of polymer substrate by electroplating lithography micro-processing techniques or laser induced and non-electrolytic plating technique [14]–[16]. The maximal PER of the double-layer grating THz polarizer increases to 60 dB [14] and the maximal average transmittance is 76% [13] in the polarization direction at 0.2–1.95 THz. The reports indicate that the PER of THz polarizers can be improved by increasing the metallic grating layer number but not decreasing the critical size of the structure.

In this paper, a THz polarizer consisting of multilayer sub-wavelength metallic gratings filled in PI film is proposed. The PI film is a low-loss THz material to achieve a high transmission in the polarization direction. The metallic sub-wavelength grating layers are parallel spaced by the PI material to obtain a remarkable PER. Influences of the grating layer number on the transmission and PER are discussed in theory. With the optimized parameters, a double-layer THz polarizer is fabricated via layered imidization processes and a high PER of 70 dB and an average transmission of 80.5% are obtained in the polarization direction at the frequency range of 0.1–2 THz.

2. Simulations

The schematic diagram of the proposed multilayer metallic grating THz polarizer is shown in Fig. 1. The structure consists of multilayer sub-wavelength metallic gratings filled in the PI film. When the incident electric field is vertical to the gratings, namely, for a transverse magnetic (TM) incidence, the THz wave will transmit through the device due to the extraordinary transmission of the sub-wavelength structure. In the other hand of transverse electric (TE) incidence, the THz wave will be rejected to transmit. Different layers of the gratings possess the same structural parameters and parallel to each other. In simulation, the metal Al with a thickness of $t = 200$ nm is chosen to form the metallic grating, and the initial structure parameters are as follows: period $p = 10\ \mu$m, grating width $w = 7\ \mu$m, and space between the layers $s = 8\ \mu$m. The finite element method (FEM) is used to calculate the transmittance in the TM and TE incidences. Absorption of the PI material is not considered in all simulations.

For the case of TM incidence, the transmittance of the THz polarizer with different layer gratings is simulated and the results are shown in Fig. 2(a). The transmission gradually decreases at the low frequency range when the layer number of the gratings is increased. However, there is a transmission peak caused by Fabry–Pérot (FP) interference at the high frequency, and the peak frequency is left shift with the increase of the grating layer number. Due to the space

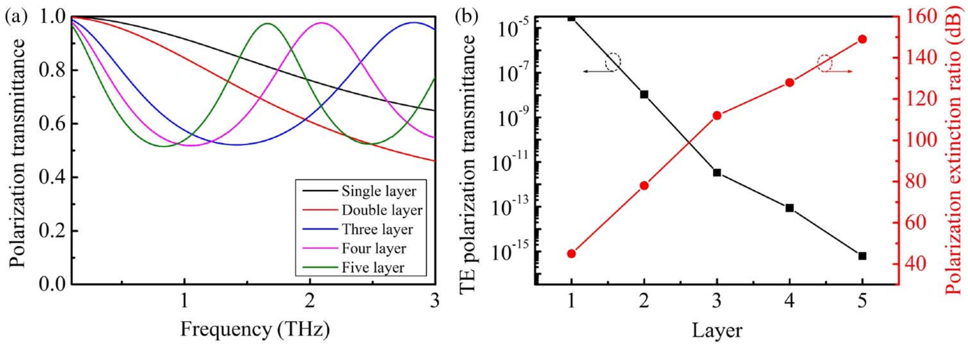

Fig. 2. Simulation results for (a) polarization transmittances at different frequency and different layer number and (b) TE polarization transmittances and PER as a function of the number of grating layers at 1 THz.

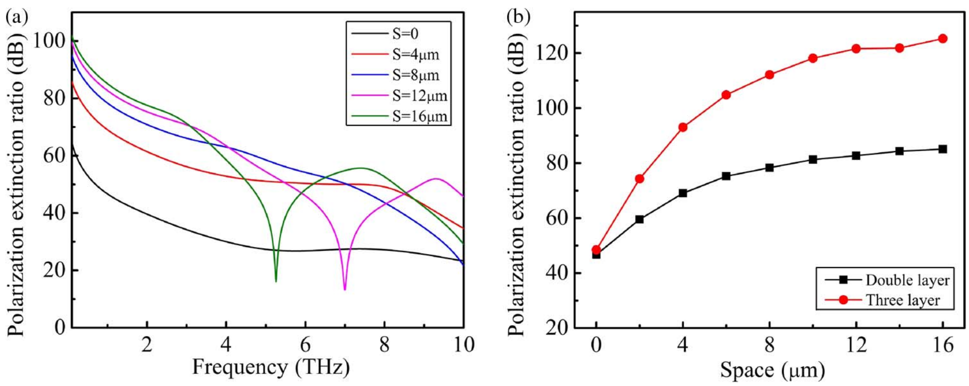

Fig. 3. (a) PER of the double-layer grating polarizer at different frequencies and different spaces. (b) PER of the double and three layer grating THz polarizers as a function of S at 1 THz.

between the grating layers is a constant, the increase of grating layer number will lead to the increase of the whole thickness of PI film, which results in a left shift of the FP resonant frequency. Benefiting from the FP resonance, the average transmittance is little changed when the layer number of gratings increases at the frequency range of 0.1–3 THz.

The transmittance of TE incidence and the PER at different layer numbers are simulated and shown in Fig. 2(b) at the frequency of 1 THz. The PER is obtained with $\mathrm{PER} = 10 \times \log_{10}(T_{TM}/T_{TE})$, where T_{TM} and T_{TE} is the transmittance of TM and TE polarized wave, respectively. With the increase of grating layer number, the transmittance of the polarizer rapidly decreases at the TE mode. Since the Fig. 2(a) shows that the T_{TM} is little changed with the grating layers, so the PER is rapidly increased with the increasing layer number, as shown in Fig. 2(b). Simultaneously, the increase of the PER is approximately linear, and the slope is about 30 dB/layer when the layer number is less than 3. However, the increase becomes slow when the grating layer number is larger than 3 since the transmittance decrease of TE incidence is slow.

For the proposed multilayer THz polarizer, the space S between different layers is the main parameter and its influence is discussed. For the polarizer with double-layers grating, the simulated PER is shown in Fig. 3(a). When the space $S = 0$, the polarizer is equal to a single-layer grating structure, which owns a minimal PER. With the increase of the space, the PER gradually increases. However, the increase of the PER becomes slower and appears a strong narrow peak at low frequency when the space S is larger, which is caused by the weaker evanescent wave coupling between the layers. When the space is larger enough, the whole thickness of the polarizer supports the FP resonance, which leads to the transmission peak at the TE mode and, accordingly, the fall of PER to an extremely low level. It is worth noting that since the resonance

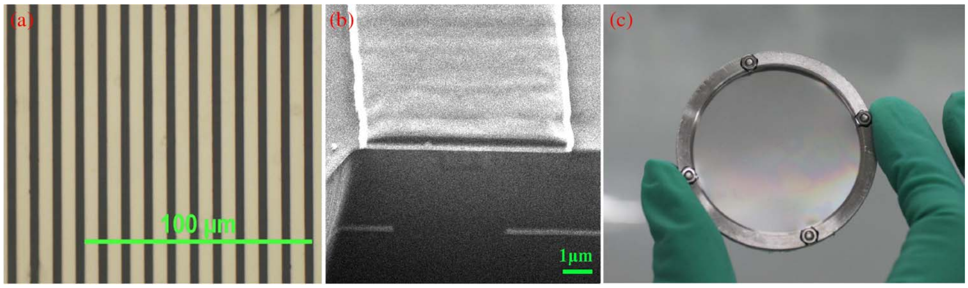

Fig. 4. (a) Optical microscope images. (b) Cross section view. (c) Packaged the double grating layer THz polarizer.

frequency point appears at different locations for TE and TM polarized waves, this F-P effect is undesired for the TE polarization transmittance, but it can modulate the TM polarization transmittance.

To obtain the optimal value of the space S, the performance of the polarizer with double and three layers grating are calculated at 1 THz. Fig. 3(b) shows that the PER of the structure with three layers grating has the same trend as that of the double one. When the space S is smaller than 8 μm, the PERs have an obvious increase. However, the curves become approximately flat when S is larger than 8 μm. The result indicates that $S = 8$ μm is the optimal parameter for the space.

3. Experiments

The polarizer was fabricated on the flexible PI film with low absorption and reflection loss at THz frequencies via layered imidization processes. In order to overcome the defect of easy folding and coiling of the thin PI film during the fabrication process, a hard silicon wafer with a thickness of 500 μm was used as a supportive substrate. By spin coating and heating, the layer of PI film with 8 μm thickness was deposited on the Si wafer. Then a layer of Al grating with parameters same as simulations was patterned on the PI film by metal deposition, photolithography and wet etching processes. After obtaining the first metallic grating layer, the fabrication steps from PI film coating to Al grating wet etching were repeated to fabricate the second metallic grating layer. The fabrication method of the multilayer structure is via layer-by-layer spin coating, heat fusion, photolithography, and visible aligning, etc., processes. In the whole process, there are two keys. One is the homogeneous fusion of the two layers of the PI films, which is achieved by heating thanks to the imidization of the PI film. Another is to keep the second metallic grating be parallel to the first layer, which is realized by a visible aligning through the observation of markers on the mask edge under the optical microscope in virtue of the transparency of the PI film. Finally, the PI film with Al grating layers was peeled off from the supportive Si substrate. The above fabrication method of the THz polarizer is compatible with conventional photolithography process.

The optical microscope image of the fabricated double-layer grating polarizer is shown in Fig. 4(a). The result indicates that the top Al grating layer is parallel to the bottom one in the perpendicular direction, and the period of the Al grating is consistent with the expected value of 10 μm. The cross section of the polarizer is imaged in Fig. 4(b) by digging a hole with the focus iron beam (FIB). It clearly shows the second layer Al grating and the bottom Al grating are immerged in the PI film. A metal ring holder with an inner diameter of 42.3 mm is used to package the double-layer grating THz polarizer, and the photograph is shown in Fig. 4(c). The effective area can be further expanded by increasing the holder size.

4. Characterization and Discussion

The polarization performance of the fabricated polarizer was measured with the THz time-domain spectroscopy (THz-TDS) under a humidity level of 3%. The control sample is a single-layer grating polarizer with the same structure parameters. For the TM transmittance, Fig. 5(a)

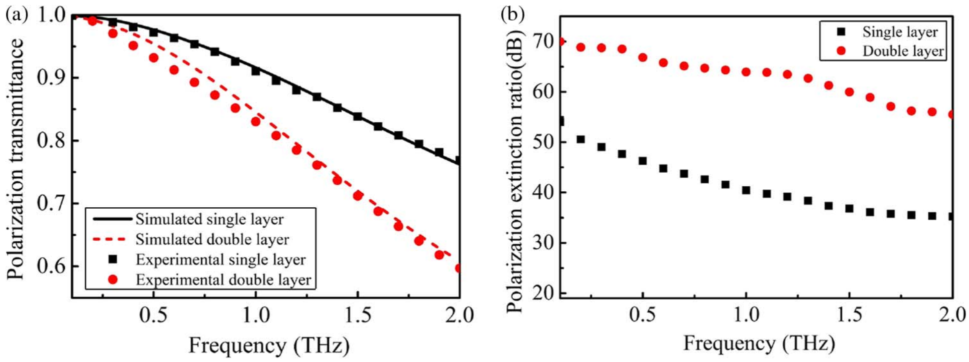

Fig. 5. (a) Simulation and experimental results of polarization transmittance and (b) PER of the experimental results for polarizer with single and double-layers.

shows that the curve of the double-layer polarizer (red circles) is lower than that of the control sample (black squares), and the average transmittances are 80.5% and 89.78% at frequency range of 0.1–2 THz, respectively. Our experimental results are almost the same as the simulation results of single-layer (black solid) and double-layer (red dash) polarizers, respectively. The reason for existing small deviation is that theoretical simulations adopted the ideal parameters. The decrease of the average TM transmittance of the double-layer polarizer is due to that the FP resonance is not excited in the measured range. In addition, the measured transmittance of the fabricated double-layer grating polarizer is much higher than that of bilayer grating THz polarizer on the Si substrate [17] and the double side grating polarizer on the polyimide film [14]. The result of the PER is plotted in Fig. 5(b). It shows that the value of the double-layer device is much higher than that of the single-layer device, and the increase is about 20 dB. At the frequency range of 0.1–2 THz, the maximal PER of the fabricated double-layer polarizer is 70 dB which is higher than the existing research results [12]–[14],[18]. The extinction ratio of the double-layer polarizer as high as 70 dB is close to the dynamic range of the THz-TDS; hence, the polarizer with three or more layer gratings is not fabricated and measured. The experimental results demonstrate that the performance of THz polarizer can be greatly enhanced by increasing the metallic sub-wavelength grating layers.

5. Conclusion

In summary, we presented a THz polarizer with high PER and transmittance using multilayer sub-wavelength metal gratings filled in a polyimide film. Influences of the layer number and the space between grating layers were discussed in simulation. Through layer-by-layer spin coating, heat fusion, and photolithography, etc., processes, the multilayer grating polarizer was fabricated. The experimental measurement demonstrated that the PER of the double-layer polarizer increased about 20 dB in comparison with the single-layer device. An average TM transmittance of 80.5% indicated that the double-layer polarizer was low-loss at the frequency range of 0.1–2.0 THz.

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