Self-polarizing terahertz liquid crystal phase shifter

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Using sub-wavelength metallic gratings as both transparent electrodes and broadband high-efficiency polarizers, a highly-compact self-polarizing phase shifter is demonstrated by electrically tuning the effective birefringence of a nematic liquid crystal cell. The metal grating polarizers ensure a good polarizing efficiency in the range of 0.2 to 2 THz. Phase shift of more than $\pi/3$ is achieved in a 256 μm-thick cell with a saturation root mean square voltage of around 130 V in this integrated device. [doi:10.1063/1.3626560]

I. INTRODUCTION

Growing attention has been attracted by the exploitation of terahertz (THz) photonics during the past two decades.[1] A number of THz applications ranging from basic spectral characterization of materials[2] to biological imaging and sensing,[3] high speed communication[4] and security applications[5] have been realized. Passive components to guide and manipulate THz waves, like polarizers,[6,7] switches[8,9] and filters[10,11] are thus in high demand. A number of materials have been investigated for these components. Among them, liquid crystal (LC) materials have raised wide interests due to their relatively large birefringence from the visible to microwave band,[12,13] as well as the continuous tunability of birefringence induced by external field.

Early works in this field are mostly on magnetically controlled LC components.[11,14] These works reached good tunability of LC birefringence by magnetic field, but the problem of its bulk and heavy setup is obvious. Therefore more works in recent years focused on electrically controlled components[15,16] for their compact size, light weight and low cost. However, there are still some challenges in this rapid growing field. Transparent electrodes are not easy to be put into practice. The widely used indium tin oxide (ITO) films in visible range show strong absorption in THz region,[17] while metal layers would also be almost opaque even with thickness down to tens of nanometers. Furthermore, a broad band polarizer is usually needed for detecting the effective refractive index change of LC, so these devices would be complicated and space-consuming as containing many components.

Herein, we present a THz LC component using sub-wavelength metallic gratings as both transparent electrodes and broadband polarizers, which makes the structure simpler and more compact with high integration of multifunctional parts. Then we demonstrated a self-polarizing THz LC phase shifter based on this design.

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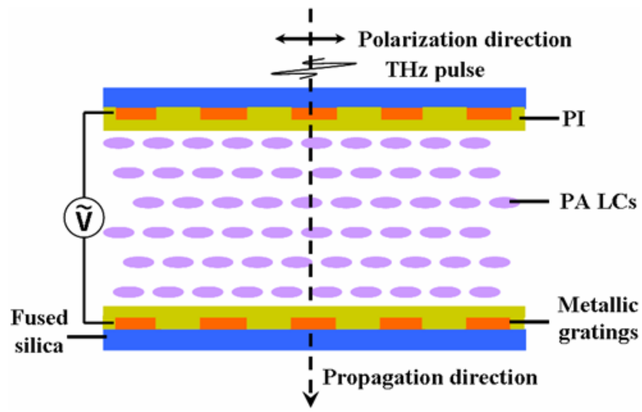

FIG. 1. (Color online) Schematic drawing of a self-polarizing THz LC component.

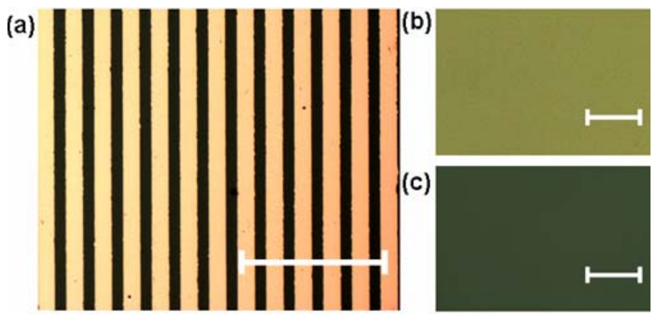

FIG. 2. (Color online) (a) is the photograph of Au gratings; (b) and (c) are the pictures of the bright and dark states, respectively, to show the LC alignment under a polarizing microscope; The scale bars in all three photographs are 100 μm.

II. DESIGN AND FABRICATION

The configuration of our device is schematically illustrated in Fig. 1. It's a cell constructed of two parallel fused silica slides (ca. 700 μm in thickness) separated by mylar films (ca. 250 μm in thickness) and filled with commercial nematic LC E7. The inner surfaces of both silica slides were covered with Au gratings and polyimide (PI) alignment layers successively. The directions of the gratings on two substrates were arranged parallel to each other. And the rubbing directions on both PI layers were set perpendicular to the Au strips, thus parallel alignment (PA) to LC was achieved. The period of the gratings was 20 μm while the linewidth was 10 μm (as shown in Fig. 2(a)), which were both far less than the wavelengths of the studied THz waves, the frequencies of which ranging from 0.2 to 2 THz. It's known that sub-wavelength metallic gratings can act as polarizers for they transmit only transverse magnetic (TM) waves (the electric field vector of incident wave parallel to the grating vector) while reflect transverse electric (TE) waves (the electric field vector of incident wave perpendicular to grating vector). Thus the gratings can be considered as a broad band polarizer. Sun *et al.* have proposed a similar idea in Ref. 6 and numerically analyzed the polarizing efficiency of the grating polarizer. Furthermore, as its high transmittance for TM waves, the metallic gratings are much more transparent than thin metal layers or ITO films, which is propitious to the performance of corresponding devices. Therefore the Au gratings here were multifunctional: both as transparent electrodes and integrated polarizers. The thickness of the gratings was set to be 30 nm for an optimum balance between transparency, conductivity and polarizing efficiency. Moreover, in such a case, the anchoring energy caused by the grating probes will be at most 1/20 of that of the rubbed PI according to Berreman's theory,[18] thus the latter one plays the dominant role in LC alignment resulting in a typically strong anchoring.

To optimize the performance of such a LC-based device, the largest refractive index change Δn (the difference between extraordinary and ordinary refractive index) of the LC layer should be achieved. At saturation voltage, all LC molecules would reorient along the direction of applied electric field, which is also the propagation direction of THz wave. As a result, the final effective refractive index is fixed at the ordinary refractive index (n_o) regardless of the polarization directions of incident waves. However, the initial refractive index of LC is intensely sensitive to polarization when no voltage applied, any contributions of ordinary wave would lead to decrease in Δn and the deterioration of device performance. To ensure a maximum Δn, the extraordinary refractive index (n_e) has to be achieved in this case by insert an additional polarizer between THz source and LC cell with its polarization direction precisely parallel to the rubbing direction of the cell. Here in our design, we integrated subwavelength Au wire grids in the cell both as effective transparent electrodes and a pair of high performance polarizers. And the grating direction was set perpendicular to the rubbing direction, thus only THz waves with E-vector parallel to the initial director of LCs are selectively transmitted by the the gratings. That is so-called the self-polarizing component. The novel design ensures that no matter what the polarization of incident wave is, maximum refractive index change can be achieved in such a structure. The structure is suitable for any kind of THz source with a highly compact size, and is widely adaptable in broadband THz applications.

III. EXPERIMENTS AND DISCUSSIONS

Based on the above design, a self-polarizing THz phase shifter is demonstrated. A THz time-domain spectroscopy (TDS) system is used for the detection of THz spectra. Before phase shifting demonstration, the exact cell gap and its uniformity were measured, for they would directly affect the value of phase shift. An interferometric method[19] was utilized for precise measurement, using an infrared light source and a high resolution optical spectrum analyzer. The cell gap is $255.72 \pm 0.69\ \mu$m on average, showing quite good uniformity. Another key factor is the alignment condition of LCs. For thick cells, it's hard to realize perfect alignment, as the cell gap exceeds the coherent length of the surface anchoring. The real condition of alignment would remarkably affect the final results. Here we graphically inspected LC alignment under a polarizing microscope with a pair of crossed polarizers. Figure 2(b) and 2(c) reveal photographs of bright state (when the director of LC is 45° to the crossed polarizers) and dark state (when the director of LC is parallel to one of the crossed polarizers) separately. As we can see, the evident contrast between the two states indicates a uniform alignment in such thick LC layer.

Thereafter we evaluated the polarizing efficiency of the cell in order to reach the self-polarizing effect for the phase shifter. We measured the transmittances of the two polarization (TM and TE) waves (T_{TM} and T_{TE}) of this sample. In this TDS system, the THz pulse is linearly polarized with normal incidence to the device. Therefore, we realized in the system the detection of transmission of the two polarization states respectively by rotating the cell by 90°. Figure 3 displays the measured transmission curves of both TE and TM waves of the LC-filled cell during the frequency range from 0.2 THz to 2 THz. As the whole cell contains two pieces of metallic wire grids with the same polarization direction, the polarization efficiency is enhanced. We can see from Fig. 3 that T_{TE} is really small during the whole spectra range, while T_{TM} waves is quite large in most of the frequency regime. The decrease in the high-frequency range may be mainly due to the absorption of metal gratings, but it would not evidently affect the polarizing efficiency at these frequencies.Through further calculation of the ratio T_{TM}/T_{TE}, we have reached an value of at least 1000 during the whole frequency range which illustrated the high polarizing efficiency of our sample, which would be suitable for wide applications.

We measured the phase shifts of the LCs by applying a square wave AC signal with frequency of 1 kHz to the cell. As we mentioned before, the THz pulse in this system is linearly polarized, so we adjusted the sample to match the condition that the incident wave is TM to the cell. In our experiment, what we directly measured is the intensity of electric field of transmitted THz pulses. The time-domain THz spectra of the empty cell and the cell with LC under certain voltages are illustrated in Fig. 4, which is a close-up from 4.25 ps to 6.25 ps, for depicting the peak shifts more clearly. Here in our device, the initial effective refractive index of the LC layer is n_e, while it would gradually turn to be n_o as applied voltage increases. So we can observe the peak of the time-domain spectrum of the LC cell gradually shifted closer to that of the empty cell, for the refractive index of

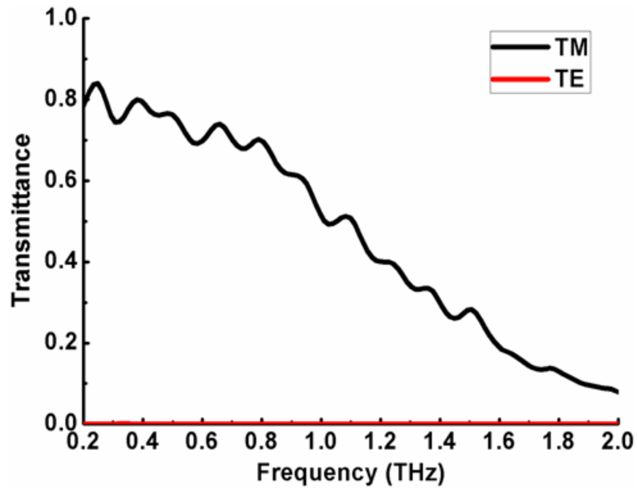

FIG. 3. The transmission curves of both TE and TM waves of the LC-filled sample measured during the frequency from 0.2 THz to 2 THz.

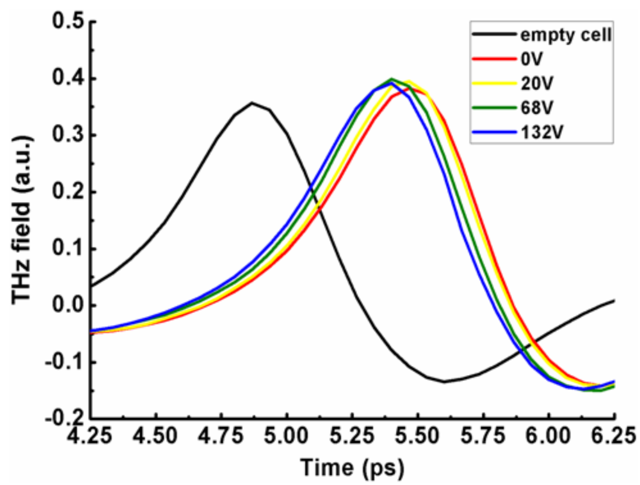

FIG. 4. Time-domain spectra of the empty cell and the LC-filled cell when applied no voltage and three specific voltages (Considering only the first transmittance peak).

the LC layer was closer to air. As the THz pulse is broad band, we need to transform the time-domain spectra into frequency domain by Fourier transformation. And the phase angle extracted from the complex electric field intensity is indeed the frequency-dependent phase change we want to get. Therefore, at each voltage point we would obtain a group of data showing the phase changes of the LC sample versus frequencies. In order to clearly depicting the phase modulation effect, we selected three specific frequencies to represent the whole effective wavelength range of detection. Figure 5 shows the phase shifts at these three frequencies as a function of the applied voltage. The dots with three shapes are measured data while the solid lines are distribution fitted curves according to the data respectively. The first voltage point under which the cell was measured is 20 V_{rms}, while we can see that the reorientation LC molecules had started already, which reveals the threshold voltage of the device is very low. As we did not get the exact value of threshold voltage, the fitted lines all pass through the origin, which does not imply that there is no threshold. The saturation voltage of this component from Fig. 5 is explicit to be around 130 V_{rms}, which is also comparatively low considering such thick cell gap. After calculation, the saturated phase shift values under the 3 frequencies are around 9°, 35° and 66° respectively to 0.28 THz, 1.18 THz and 1.88 THz. While comparing with the theoretical phase shift values at these frequencies,[20] we found the experimental

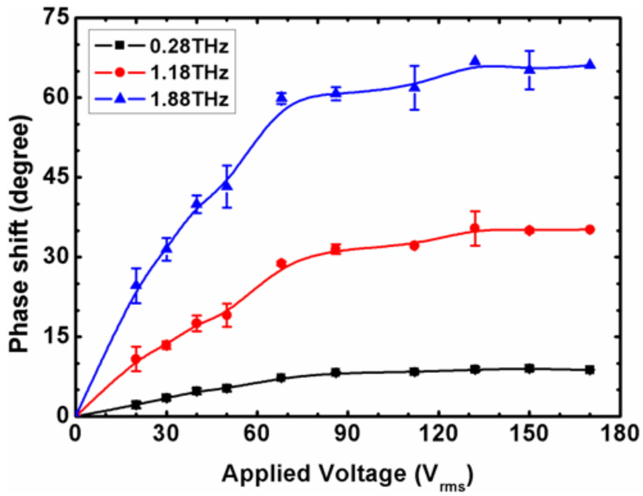

FIG. 5. (Color online) Phase shift as a function of driving voltage at 3 frequencies.

results are a little smaller than that of the calculated values. The reasons of this discrepancy could be mainly attributed to two points. One is the imperfect alignment of LCs in thick cells, which will decrease the initial effective refractive index (should be n_e in perfect case). The other is the shape of electrodes, which is separated from each other, causing the non-uniform distribution of applied electric field in the cell, e.g. the fringing field effects. Thus the alignment would also not be ideal when high voltage is applied, causing increase in the effective refractive index (should be n_o under ideal circumstance). These two factors both decrease the refractive index changing during the process, causing the discrepancy between experimental and theoretical values of phase shifts. To stabilize the initial LC alignment, a polymer network might be employed in the cell without degrading its scattering-free status in THz region. The fringe field effect also could be suppressed by using finer gratings as electrodes.

In our experiments, Au wire grids with different geometrical features such as pitch and line width, have also been demonstrated. Excellent performances similar to the device shown above have been achieved. It suggests a wide tolerance of geometrical design of the structures. Furthermore, the state-of-the-art nano and micro fabrication techniques might facilitate the exploring of some novel LC based THz devices with more amazing performance. Because polarizer and electrode are two fundamental elements, our grating structure provides the possibility to measure material parameters in such a compact setup. So far, many terahertz results are not quite consistent. Precise measurements are thus desired to resolve the discrepancy between theory and experiment.

IV. CONCLUSION

In summary, we proposed and demonstrated a self-polarizing THz phase shifter based on LC technology. A sub-wavelength metal grating acts as both transparent electrodes and a built-in THz polarizer to control the input waves' polarization while the LC further adjusts its phase retardation driven by an AC electric field. A large phase shift up to 66° is achieved. Given its advantages of comparatively low threshold voltage below 20 V_{rms} and low saturation voltage around 130 V_{rms}, we believe this kind of component should have very promising applications in compact and broadband tunable THz devices.

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