Electrically controlled optical choppers based on holographic polymer dispersed liquid crystal gratings

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An electrically controlled optical chopper based on switchable holographic polymer dispersed liquid crystal (H-PDLC) gratings is demonstrated through a programmable, adjustable, and periodic external driving source. Compared with traditional mechanical optical choppers, the H-PDLC chopper exhibits many advantages, including faster response time, less waveform deformation, as well as easier integration, control, and fabrication, to name a few. Its excellent performance makes the device potentially useful in frequency modulation optical systems, such as frequency division multiplexed microscopy system.

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Holographic polymer dispersed liquid crystal (H-PDLC) has been receiving intensive attention in photonics since Sutherland *et al.* first reported about it in 1993[1]. H-PDLC-based gratings are tunable and switchable[2−5] because the refractive index matching between the polymer bonder and the liquid crystal droplets can be adjusted by a suitable external driving voltage. Thus, many H-PDLC-based devices have been demonstrated, such as lenses[6−8], optical switches[3,4], optical attenuators[9,10], and dynamic gain equalizers[11]. H-PDLC-based devices have high diffraction efficiency and fast response time, and are easy to fabricate. Therefore, these devices have been extended to other applications, including information storage[12], sensing[13], lasing[14−16], photonic crystals[17−19], and other optical devices[20−23].

Majority of the H-PDLC-based opto-electronic devices that have been conceived and implemented only take advantage of the basic characteristics of H-PDLC Bragg gratings, such as excellent wavelength or angle selectivity, to realize the intensity modulation or wavelength division. H-PDLC grating can modulate the input light to the "ON" or "OFF" state, as allowing it to act as an optical chopper through the application of a periodic driving source to replace the conventional mechanical optical choppers.

Generally speaking, a conventional optical chopper consists of a slotted rotating disc, which modulates the light beam. A conventional chopper design has slow response time and is prone to mechanical deformation. Mechanical choppers, especially those with multiple beams modulation, cannot easily achieve real-time, small-scale, and integrated design. H-PDLC choppers, on the other hand, can overcome these limitations and exhibit several advantages, such as faster response time (less than 1 ms), easier fabrication and integration, etc. In this letter, we conceive and demonstrate experimentally an electrically controlled chopper based on H-PDLC. The proposed chopper not only has the potential to replace mechanical chopper in several conventional applications, such as beam modulation, it is also suitable for a number of emerging applications, such as in frequency division multiplexed confocal microscopes[24].

H-PDLC grating works as an electrically controlled switch. At the "OFF" state, the H-PDLC phase grating formed by the mismatch of the refractive index between the liquid crystal droplet and polymer bonder diffracts the incoming linearly polarized light. However, when a suitable electric field is applied, the polarization directions of all liquid crystal (LC) molecular directors are reoriented along the electric field direction. In particular, the Bragg grating disappears when the ordinary refractive index of the LC matches the refractive index of the surrounding polymer. In this case, the incident laser beam transmits the cell directly without diffraction, corresponding to the "ON" state. Therefore, by applying a proper electric field, H-PDLC grating can be switched between the "ON" and "OFF" states. Furthermore, given that such kind of switching can be realized with nearly 100% efficiency at fast speed[2−4] without the risk of scattering loss[25], the H-PDLC-based switch can be used as a fast speed chopper.

The fabrication of H-PDLC grating with high diffraction efficiency and fast switch time is an important step in realizing the H-PDLC-based optical chopper. In our experiment, H-PDLC gratings were fabricated from a formulation of 39.9 wt.-% LC, TEB300 (Tsing-Hua Yawang), 39.9 wt.-% monomer, EB8301(UCB), 8 wt.-% crosslinking monomer, N-vinylpyrrollidone (NVP) (Sigma-Aldrich), 0.07 wt.-% photoinitiator, rose Bengal (RB) (Sigma-Aldrich), 0.13 wt.-% coinitiator, N-phenylglycine (NPG) (Sigma-Aldrich), and 12 wt.-% surfactant, S-271 (ChemService). The LC TEB300 has an ordinary refractive index of $n_o = 1.511$ and a birefringence of $\Delta n = 0.168$ at 589 nm. All the materials were mechanically blended according to the appropriate weight ratios; these were stirred in an ultrasonic cleaner

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at 65 °C to form a homogeneous mixture in dark condition. Afterwards, the mixture was sandwiched in a cell, which was assembled by two pieces of indium-tin-oxide (ITO) glass, and then subjected to holographic exposure (Fig. 1). In brief, an Ar^+ laser beam (514 nm) was collimated and then divided into two beams that can intersect and interfere with each other. The interference pattern was recorded in the LC cell. Each beam had an intensity of 10−20 mW/cm^2 on the sample, and the exposure time was 60−120 s. After exposure, the sample was further cured for 5 min by a mercury lamp to ensure the complete polymerization of prepolymer. The thickness of the samples can be adjusted between 8−20 μm using different diameter bead spacers between the two pieces of ITO-coated glasses.

In our initial experiments, the diffraction efficiency was more than 50% for most samples. Maximum rate reached 80% with spatial frequencies ranging from 600 to 1200 lines/mm. The measured effective voltage was less than 10 V/μm. However, after the switching, there was a residual diffraction efficiency of 5%–10% due to the mismatch refractive indices between the LC and polymer matrix in the experiments. The fabricated H-PDLC samples are not perfect in terms of diffraction efficiency and extinction ratio between the "ON" and "OFF" states, but it is good enough for us to conduct the optical chopping experiment. Details of the experiment will be described below. Based on the performance

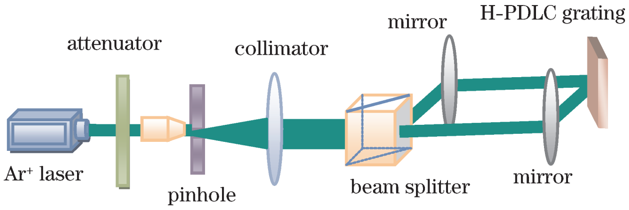

Fig. 1. Experimental setup used in fabricating the H-PDLC.

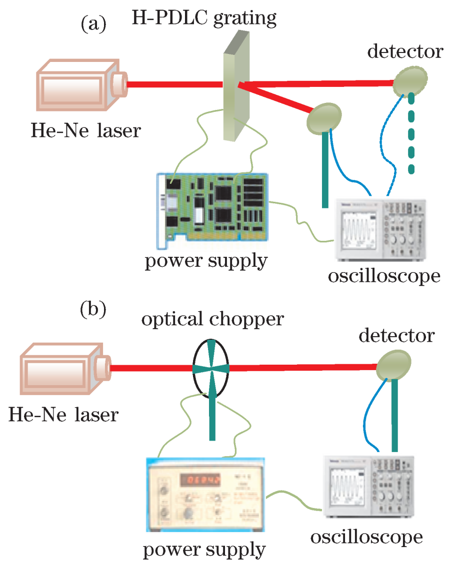

Fig. 2. Measurement setup for (a) the H-PDLC chopper and (b) the mechanical chopper.

data reported by Refs. [2−4], we believe that better performance can be achieved in the future.

A specific external driving power source designed for the H-PDLC cell is necessary in achieving an effective chopping function. The driving power source and its controller should satisfy three requirements. First, the power source should generate about 1-kHz alternating current (AC) voltage to drive the H-PDLC gratings; second, the 1-kHz AC signal can be enveloped with carrying frequency, for example, 250 or 400 Hz pulse group; third, the power source can be controlled to have variable duty ratios and adjustable output voltages from 100 to 400 V.

Experiments to test the feasibility of H-PDLC chopper were conducted after the driving power was completed. Figures 2(a) and (b) represent the measurement setup of

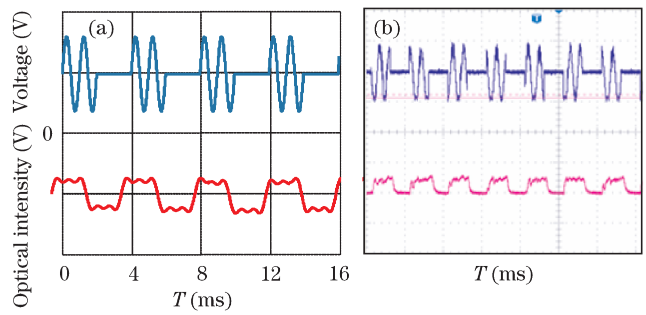

Fig. 3. (a) Simulation and (b) experimental results of the H-PDLC Chopper in generating a rectangular wave with 250 Hz.

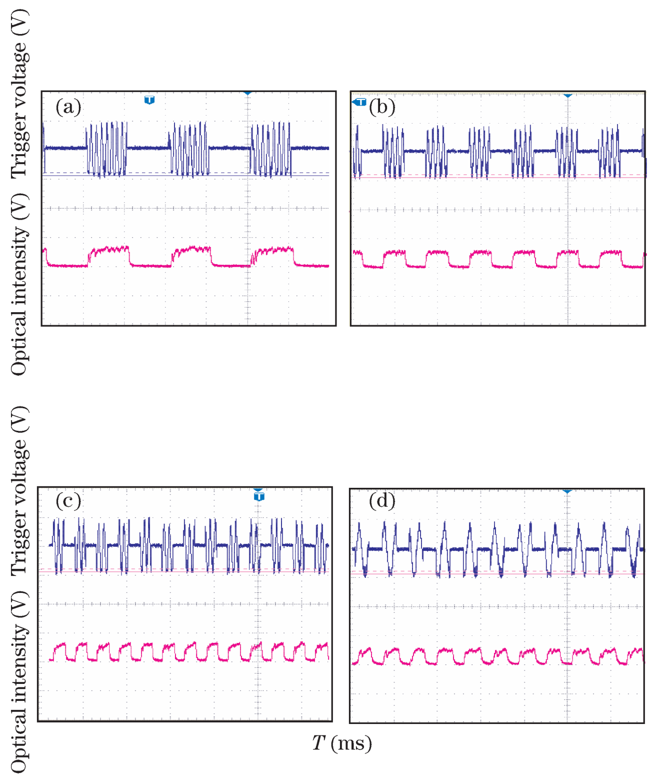

Fig. 4. Experimental H-PDLC rectangular wave choppers working at (a) 50 HZ, 10 ms/unit; (b) 100 HZ, 10 ms/unit; (c) 200 HZ, 10 ms/unit; (d) 400 HZ, 4 ms/unit.

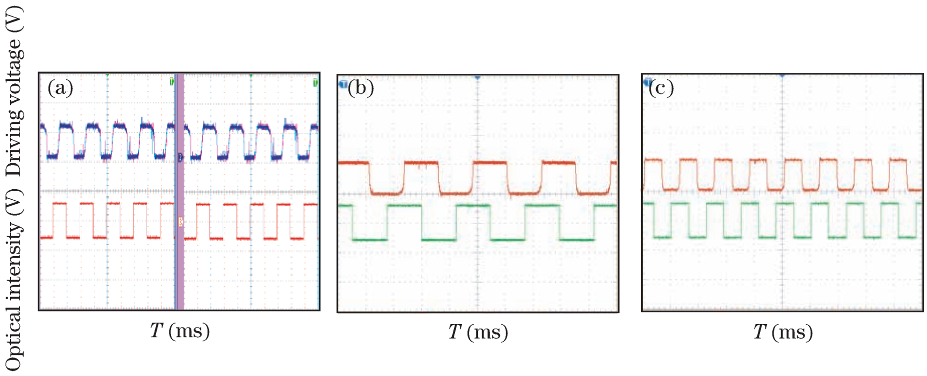

Fig. 5. Standard experimental curves of the mechanical optical chopper (a) 50 HZ, 10 ms/unit; (b) 100 HZ, 4 ms/unit; (c) 200 HZ, 4 ms/unit. Upper lines indicate the optical intensity curves, lower lines indicate the synchronous references.

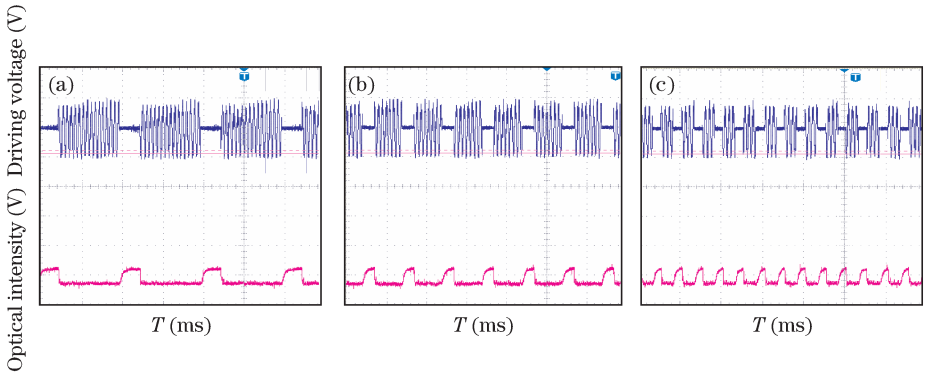

Fig. 6. H-PDLC chopper working with different duty cycles and frequencies: (a) 3:1 at 50 Hz, (b) 7:3 at 100 Hz, and (c) 3:2 at 200 Hz.

the H-PDLC chopper and the mechanical optical chopper, respectively. A He-Ne laser (633 nm) was incident on the H-PDLC grating sample with the exact Bragg angle of 28.6 ° (corresponding to a spatial frequency of 780 lines/mm) (Fig. 2(a)). The photo detector collected the diffraction or transmission signal and fed it into a TEK oscilloscope. At the same time, the external power supply used to generate the electricity field for the H-PDLC chopper was also connected to the other channel of the oscilloscope for reference and synchronization. For comparison, the performance of the mechanical chopper was also measured using the setup shown in Fig. 2(b).

We studied the H-PDLC chopper to generate a rectangular waveform. The driving voltage was 1-KHz AC pulse signal. The desired chopper frequency was 250 Hz. Figure 3(a) shows the simulated results. In the simulation, we assumed that the horizontal axis was the time axis with a unit of 4 ms, the duty cycle was 1:1, and the duration covered two basic cycles of a 1-kHz sine wave. The H-PDLC-based optical chopper was at the transmission state when voltage was applied. Contrarily, it was in the block state without the applied electric field. Figure 3(b) shows that the experimental result agrees with the simulation, thereby confirms the feasibility of our proposed H-PDLC-based optical chopper.

A series of experiments with different frequencies was conducted. Figures 4(a)−(d) show the results of H-PDLC chopper working at 50, 100, 200, and 400 Hz, respectively. The trigger voltage wave is shown on the upper curve, and the lower curve is the optical intensity modulation. The nearly standard and stable rectangular modulation of the optical intensity can be achieved in all frequencies. Response time is fast at $\tau_{\rm on} = 80$ μs and $\tau_{\rm off} = 0.59$ ms. Figure 5 shows the typical curve of the mechanical chopper working at 50, 100, and 200 Hz, individually. It can be seen that the optical modulation signal is much slower than the synchronous reference signal. The time differences between the upper and lower lines are shown at "ms" magnitude. It also brings some extent waveform deformation (i.e., not a perfect rectangular waveform) caused by slow response of a mechanical slot blade. Moreover, the mechanical chopper must accelerate the ringing speed even through changing a blade to obtain higher working frequency. The frequency of the H-PDLC chopper is controlled by changing the operation parameter within the computer operation window. The experimental results show clearly the advantages of using H-PDLC gratings as optical choppers, including faster response time, less waveform deformation, and easier operation.

Another unique property of a H-PDLC chopper compared with mechanical one is the ability of the driving source to be tuned by a controller. Figure 6 shows the H-PDLC chopper working with different duty cycles; the upper curves are the driving voltages as function of time and the lower curves are the detected optical signals. The results are the detection of the transmission beams instead of diffraction; the "ON" and "OFF" states of the lower curves are reversed as compared with those in Fig. 4.

Even with the advantages of faster response time and easier operation, the H-PDLC-based chopper still has a number of weak points. First, the achieved maximum frequency (about 13889 Hz) is limited by the response time of H-PDLC (i.e., 36 μs[22]). Second, the modulation depth highly depends on the diffraction efficiency and LC droplet rotation angle. If the efficiency cannot reach 1, the beam cannot be fully cut off. Our initial experiment achieved a maximum 70%−80% efficiency. At any rate, this efficiency is good enough to demonstrate the feasibility of our proposed H-PDLC-based chopper. Given that an efficiency rate of almost 100% has been reported by other groups[2−5], we believe that our proposed approach has the potential to be used in the real system, such as frequency division multiplexed confocal microscope[24].

In conclusion, we have experimentally demonstrated an electrically controlled optical chopper based on H-PDLC grating. Using the H-PDLC chopper, a stable and controllable square waveform can be generated in a compatible, fast, and integrated way. Furthermore, the theoretical and experimental chopping results at different duty cycles have also been reported. These results show clearly the advantages of the H-PDLC-based chopper, including faster response time, smaller waveform deformation, and easier operation. Finally, future directions, including the improvement of diffraction efficiency and the potential applications of this device (e.g., frequency division multiplexed confocal microscopes) have also been addressed.

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