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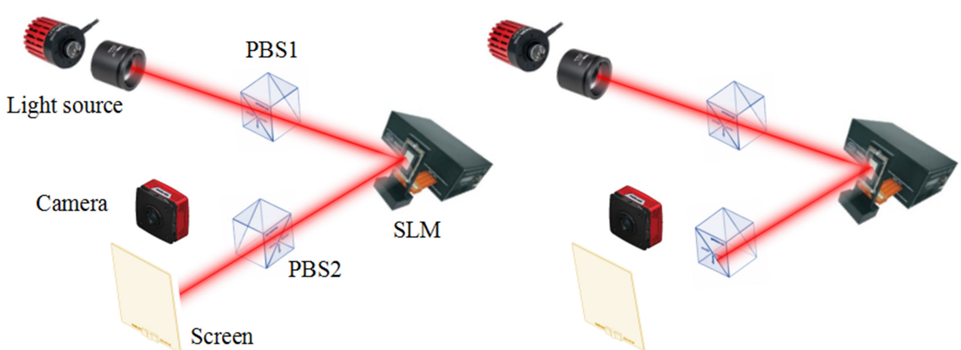

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Adjustable Optical Slit Based on the Phase Type Spatial Light Modulator

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Abstract: In this paper, we propose an adjustable optical slit based on a phase type spatial light modulator (SLM). The adjustable optical slit consists of two polarized beam splitters and one SLM. The SLM is used to modulate the phase of light. A phase grayscale with specific structure is produced, where the middle phase is 0 and the phase on both sides is π. By changing the width of the slit grayscale, we can adjust the width of the slit easily. Our experiment shows that one-dimensional (1-D) slit and 2-D mask can be realized and the slit width can be tuned accordingly. The results verify its feasibility. The adjustment accuracy of slit can reach several microns, and the slit can also be laterally translated. The proposed device can be used not only in optical system or holographic display to improve the quality of the image, but also in spectrometers to select the specific spectral feature.

Index Terms: Optical slit, spatial light modulator, holographic display.

1. Introduction

Adjustable optical slits have found widespread applications in optical systems, such as optical measurement, masking, spectroscopic imaging and spectroscopy [1]–[3]. The traditional way to design an adjustable slit is by changing the distance of two blades mechanically [4]–[5]. However, due to mechanical actuation, the width change of the slit is not accurate and the tuning speed is slow. So the mechanical silts are very bulky for incorporation into miniaturized optical systems. Recently years, liquid devices have attracted much attentions due to the advantages of polarization-independence, high transmittance, and fast response [6]–[10]. In 2015, an electrowetting-based adjustable optical slit was proposed. By changing the voltage applied on the device, the width of the slit can be tuned from ~160 μm to ~570 μm [11]. In 2016, an optofluidic slit was proposed by precisely controlling the movement of the liquid interfaces of two highly opaque ink droplets [12]. The slit widths ranging from about 1 mm to 45 mm can be digitally set with dimensions defined by micro-structured transparent ITO electrodes. And the slit can be used to select the different bands of the spectrum. However, the gravity effect is unavoidable when the liquid slits is placed in vertical position, and the repeatability of the device is reaming to be solved. Therefore, an accuracy and fast controlled optical slit is needed to be studied. Recently, the spatial light modulator (SLM) has

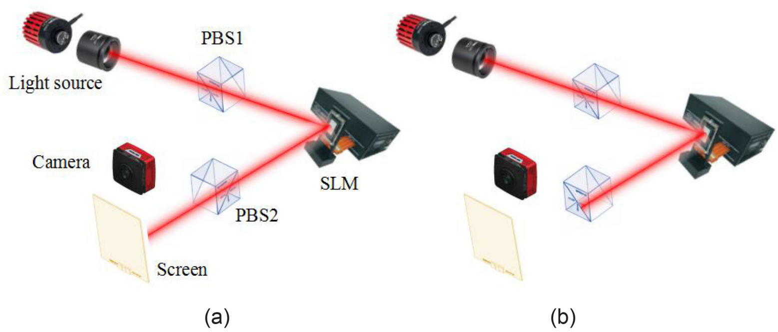


Fig. 1. Principle of the proposed adjustable slit. (a) Initial state; (b) state when loading phase π to the SLM.

drawn much attention owing to its advantages of programmability, light weight and high resolution [13]–[18]. As an active optical element, the SLM not only can modulate the amplitude information of the light wave, but also can modulate the phase information of the light.

In this paper, we propose an adjustable optical slit based on the phase type SLM. By changing the phase information encoded on the SLM, the polarized state of the polarized light can be changed accordingly. By loading the specific phase information on the SLM, the device can realize the function of optical slit. Compared with other existing slits, our proposed slit can not only realize function of adjustable slit without mechanical operation, but also the shape of the slit can be designed according to the requirements. To the best of our knowledge, the shape of the adjustable slit cannot be changed easily. Therefore, the proposed new slit has unique advantages.

2. Structure and Operating Principle

The principle of the proposed adjustable slit has been depicted in Fig. 1. It consists of two beam splitters (PBSs) and a phase type SLM. The SLM is located between two PBSs and the polarizations of two PBSs are in the same direction. In the initial state, when light passes through PBS1, no phase is loaded on the SLM, so the light passes through SLM and PBS2 and the light can be detected, as shown in Fig. 1(a). When phase π is loaded on the SLM, the light passes through PBS1, then the polarization of the light is changed after passing through the SLM, so light cannot pass through PBS2 in the same direction, as shown in Fig. 1(b). At this time, the SLM plays a role as a half-wave plate. In this way, the device can realize the function of the optical switch. When we control the size of phase π that loaded on the SLM, the size of the optical switch can be adjusted easily. Besides, by loading different phases on the SLM, the intensity of light will change accordingly. So a specific phase is designed and loaded on the SLM to realize the function of adjustable slit. As shown in Fig. 2, the phase consists of two different phase values, where the middle part is with phase 0, and the both sides are with phase π. When light passes through PBS1 and the SLM, only middle light can pass through PBS2 and be detected by the camera, so the slit light can be detected. When the size of the middle phase changes, the width of the slit changes accordingly. In this way, the device can achieve the function of an adjustable optical slit.

3. Experiment and Discussion

In our experiment, we use a red LED light with $\lambda = 632$ nm as the light source. A phase type SLM is used with a pixel pitch of 8 μm. The panel size of the SLM is 15.36 mm $\times$ 8.64 mm and the resolution is 1920 $\times$ 1080 pixels. The minimum precision of the pixel size for red, green and blue colors is $\sim$0.1 μm. In the experiment, the pixel size of the SLM is 8 μm. The fill factor of the SLM is $>$87% and the diffraction efficiency is 60%. In order to obtain the phase modulation characteristics

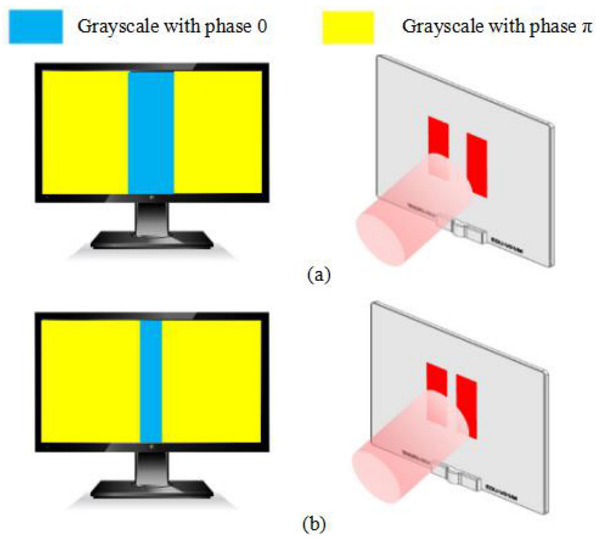


Fig. 2. Grayscales of slit with different sizes. (a) Slit size 1; (b) Slit size 2.

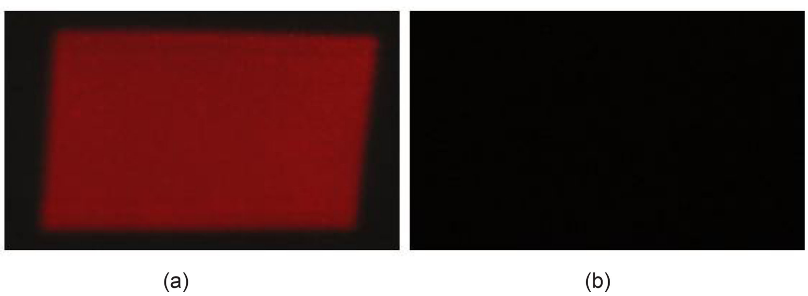


Fig. 3. Results when different phases are loaded on the SLM. (a) Phase 0; (b) phase π.

of the SLM, we measured the wavelength modulation range of the SLM by using the isometric interferometry firstly. The specific operation is as follows: the light from the same laser is divided into two beams, one beam incidents on the SLM and the other beam incidents on the mirror. The beam reflected by the SLM and the beam reflected by the mirror interfere in the optical path. By loading different grayscale images on the SLM, different interference fringes can be obtained to calculate the phase modulation range of the light. Then we record the gray value when the phase modulation of the SLM is 0 and π, respectively. The phase pattern of the slit is generated by using MATLAB software and then loaded on the SLM in real time. In the initial state, phase 0 is loaded on the SLM, so there is no phase modulation. The light passes through PBS1, SLM and PBS2, then the light can be detected, as shown in Fig. 3(a). When phase π is loaded on the SLM, the light passes through PBS1, and the polarization of the light is changed after passing through the SLM, so no light can be detected by CCD camera, as shown in Fig. 3(b).

Then a new phase grayscale is produced with size 1920×1080. It consists of two parts, where the middle part is with phase 0, and the both sides are with phase π. Figs. 4(a)–(d) are phase grayscales when the size of the slit changes. When the SLM is loaded the phase grayscale and illuminated by light source, only middle slit light which illuminates the phase 0 can pass through PBS2, other light which illuminates phase π cannot pass through PBS2. So, the CCD camera can detect the optical slit light. By changing the width of the slit grayscale, we can adjust the width of the slit light detected by the camera, and the results are shown in Fig. 5.

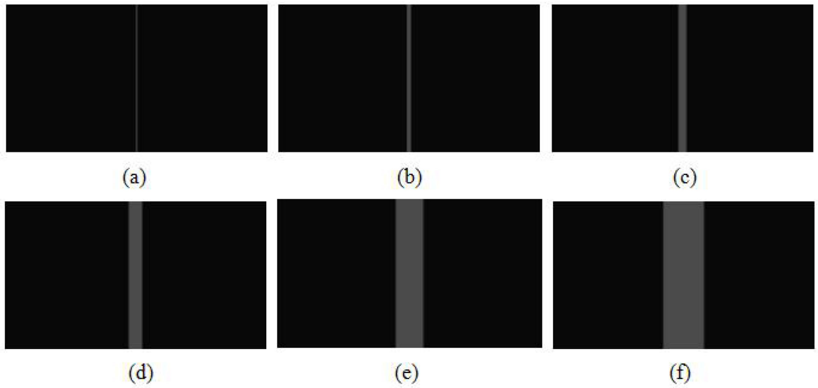


Fig. 4. Phase grayscale when the width of slit changes. (a) 10 pixels; (b) 30 pixels; (c) 60 pixels; (d) 100 pixels; (e) 200 pixels; (f) 300 pixels.

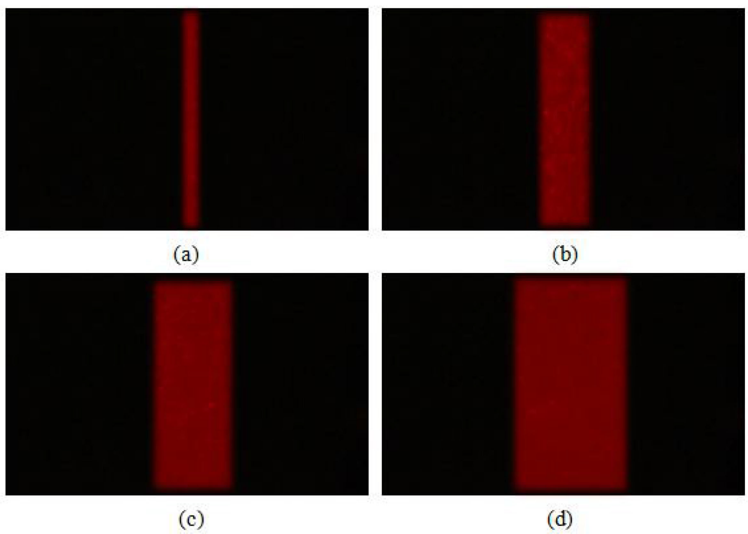


Fig. 5. Results of the slit in the vertical direction. (a)–(d) are four different width slits ranging from 100 pixels to 600 pixels.

From the results we can see that the device can realize the function of an adjustable slit. The slit width changes with the size of the middle slit grayscale accordingly. When the width of the middle slit grayscale is 0, the slit can realize the light fully closed state, and when the size of the middle grayscale is 1920×1080, the slit can realize the fully open state. As the pixel size of the SLM is 8 μm, the accuracy of the slit can be accurate to micrometers. In the experiment, the slit we designed is in the vertical direction, and we also design a horizontal slit as required. Fig. 6 is the result of horizontal slit. The width of the horizontal slit can be adjusted easily by changing the phase grayscale.

In the second experiment, a two-dimensional mask is designed. Fig. 7 is the phase grayscale of the two-dimensional masks, and the results are shown in Fig. 8. From the results we can see that the device can realize the function of adjustable slit both in the horizontal and vertical direction. Nowadays, the mechanical slits in the market usually adjust luminous flux in one-dimensional direction, and it is difficult to achieve adjustment in two-dimensional directions simultaneously. While the proposed adjustable slit can realize two-dimensional adjustment by controlling the phase grayscale.

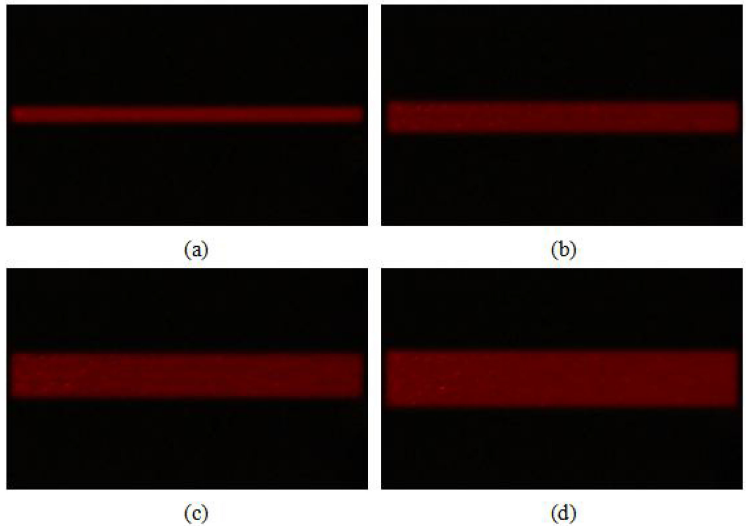


Fig. 6. Results of the horizontal slit. (a)–(d) are four different width slits.

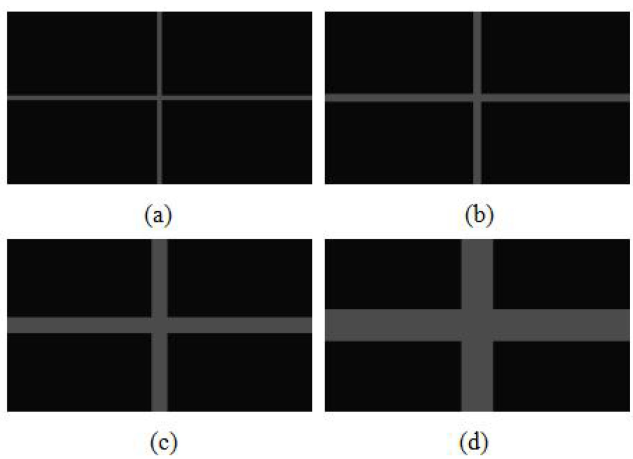


Fig. 7. Phase grayscale of the two-dimensional masks when the width of slit changes. (a) 30 × 30 pixels; (b) 50 × 50 pixels; (c) 100 × 100 pixels; (d) 200 × 200 pixels.

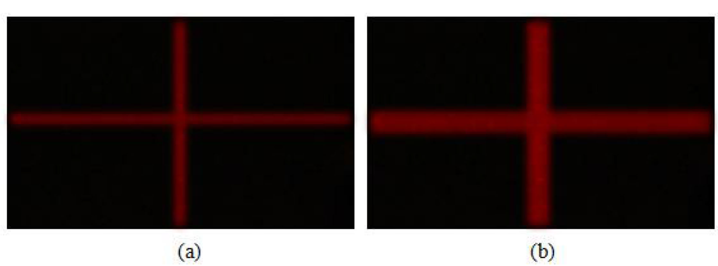


Fig. 8. Results of the adjustable slit when the size of the middle grayscale changes. (a) 100 × 100; (b) 240 × 240.

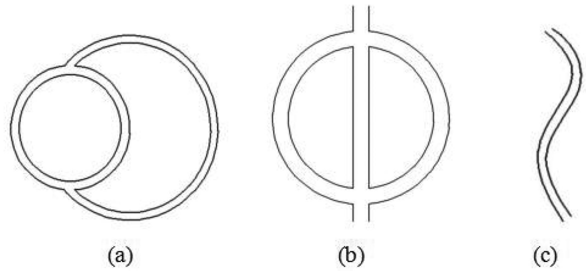


Fig. 9. Different shapes of the slits. (a) Shape 1; (b) shape 2; (c) shape 3.

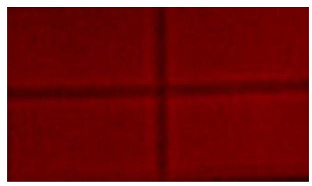


Fig. 10. Result of the filter.

Compared to other adjustable slits, the proposed slit has certain advantages. For example, the width of the slit is changed by adjusting the phase grayscale loading on the SLM, which is more accurate and easier to be operated. The shape of the slit can be designed to arcuate slit, linear slit and other shapes by changing the shape of the phase grayscale (as shown in Fig. 9), so the slit has a broader application. Besides, the response time of the slit is fast, which determined by the refresh rate of the SLM. In the experiment, the refresh rate of the SLM is 60 HZ, so the width of the slit can be adjusted with refresh 60 times in one second. As the pixel pitch of the SLM is 8 μm, the adjustment accuracy of slit is 8 μm. The light source we used in the experiment is LED, when the light source is polarized, one PBS is needed. The light illuminates the SLM and is modulated, then the device can realize the function of the optical slit if the polarization direction of the light is perpendicular to the PBS. The SLM panel size is 15.36 mm $\times$ 8.64 mm, meaning the width of the slit can range from 0 to 15.36 mm. Moreover, the slit can also be laterally translated, which can be used in spectrometers to select the specific spectral feature. In this paper, the middle phase loaded on the SLM is 0 and the phase on both sides is π. When the middle phase is changed to π and the phase on both sides becomes 0, the device can also achieve the role of filter, as shown in Fig. 10. Then the light can be filtered specifically.

The proposed device has a wide range of applications. We know that SLM is widely used in fields such as holographic imaging and optical zoom system. However, due to the influence of the pixel structure of the SLM itself, the reconstructed image is disturbed by high-order diffraction light and high-order diffraction images. In order to verify the application of the proposed device, we use it in an optical zoom system, as shown in Fig. 11. In the system, the SLM1 is used as a zoom lens, by adjusting the focal length of the lens loaded on the SLM1, the system can realize the function of zoom lens, the results is shown in Fig. 12(a). Fig. 12(b) is the partially enlarged result. From the results we can see that the image is disturbed by the high-order images. Then we use the proposed adjustable slit in the optical zoom system, the device is placed between the SLM1 and the receiving screen, and the result is shown in Fig. 12(c). From the result we can see the undesirable light is eliminated in the image by using the device. Since the zero-order light is eliminated, the brightness of the image is low in the result, but this is a common problem in the method of eliminating the undesirable light. Besides, the light intensity of the image is decreased since the diffraction efficiency is 60%. The energy of the image can be increased by using the other methods, such as loading a blazed grating on the SLM [19]–[24]. With the development and progress of the process, the

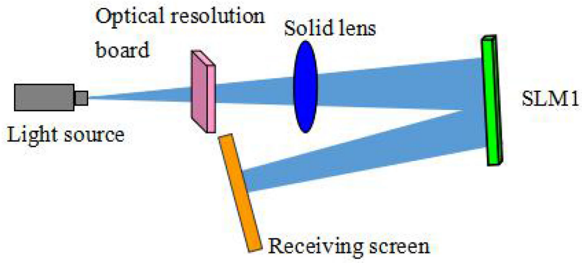
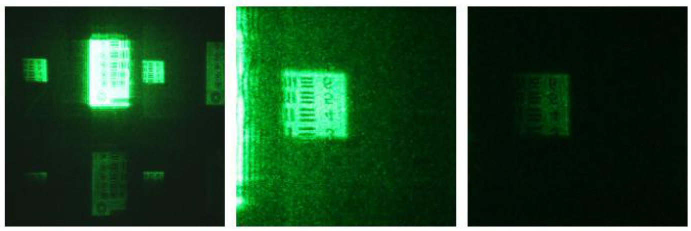


Fig. 11. Optical zoom system.



(a) (b) (c)

Fig. 12. Experimental results. (a) result of the optical zoom system without using the proposed adjustable slit; (b) partially enlarged result of result (a); (c) result of the optical zoom system using the proposed adjustable slit.

SLM with higher diffraction efficiency can be realized, then the light intensity of the image can be improved further. When the image is zoomed, the size of the slit can be adjusted to eliminate the high-order light and high-order images, so the adjustable slit has an absolute application advantage in the zoom system. Moreover, the proposed adjustable slit can be also used in the holographic display to eliminate the high-order diffraction light and the high-order diffraction image. We know that in order to improve the quality of the reconstructed image in the holographic system, two or more SLMs are needed in the system, so we can consider applying the slit by using one of SLMs in the holographic system. Besides, we can consider combining the phase of the slit with the phase hologram of the object to realize the high quality reconstruction. Color overlay can be achieved by using space multiplexing or time multiplexing method based on the visual persistence effect with a phase SLM [25]–[27]. In the experiment, due to the pixel structure of the SLM, the result is disturbed by the high-order diffraction light and diffraction images, as shown in Fig. 12(a). At present, we have completed the preliminary exploration experiment of holographic display, and we will continue our work in the next research. The adjustable optical slit is produced based on two PBSs and an SLM. In the experiment, the angle offset is less than 10 degrees. Compared with other existing slits, our proposed slit can not only realize function of adjustable slit without mechanical operation, but also the shape of the slit can be designed according to the requirements. Experimental results verify the feasibility of the proposed slit. To the best of our knowledge, the shape of the adjustable slit cannot be changed easily. The advantage of this paper is the simple structure of the device and its controllable shape. The minimum pixel size currently available on the market can reach 3.74 μm. We believe that with the improvement of the process, the pixel size of the SLM can be made smaller in the future.

4. Conclusions

In conclusion, we propose an adjustable optical slit based on the phase type SLM. By adjusting the phase grayscale loaded on the SLM, the width of the optical slit can be adjusted easily. Our experiment shows that one-dimensional slit and two-dimensional mask can be realized and the slit width can be tuned accordingly. The adjustment accuracy of slit can reach micron. Experimental results have verified the proposed device can be used in the optical zoom system to improve the quality of the image. Overall, the proposed adjustable optical slit has wide applications in optical measurement, masking, spectroscopic imaging and spectroscopy.

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