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An invertible wavefront switching system with a high extinction ratio

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HIGHLIGHTS

- A wavefront switch with higher extinction ratio is realized.
- Effective switch with lower control power is realized.
- Control beam can be used to control either ON or OFF signal.

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ABSTRACT

We report the development of an invertible wavefront switching system, consisting of a spatial light modulator (SLM), a diffuser, a signal beam, and a control beam. The shaped optical signal beam can be switched between on and off states by disturbing the diffuser with a control beam via thermo-optic effect. During the wavefront shaping process, the extinction ratio of the signal beam is iteratively optimized. We demonstrate a high extinction ratio of nearly 20. In addition, when the control beam is on, a switch with either on or off state can be configured to via encoding different wavefront patterns to the signal beam. This work potentially advances many physical or bio-medical applications employing all-optical switches.

1. Introduction

Wavefront encoding shows advantages in overcoming strong scattering in turbid media and has broad physical, chemical and bio-medical applications [1–10]. Via encoding the incident wavefront to match the random phase distortion in a diffuser, the transmitted or reflected optical power can be greatly enhanced [1,8]. A disturbance to the diffuser may destruct the optimized wavefront, leading to an "off state" of light power. Recently, Strudley et al have applied this idea to build a switchable wavefront encoding system [11]. A control beam disturbs a diffuser and induces a decrease of signal power (off state). In addition, when the wavefront is optimized with the control beam on, removal of the control beam will lead to a decrease of signal power. As a result, turning on the control beam can switch the signal beam either on or off. Although promising, a remaining challenge is that the extinction ratio between the on and off states needs further improvement. A high extinction ratio is a key for an effective switch. It may also allow the use of a low control power, reducing the risk of optical damage [12–14]. Therefore, the development of a new method to further increase the extinction ratio would be valuable for broadening the application of the switchable wavefront encoding technique.

Here, we report a new invertible wavefront switching system that achieves a high extinction ratio between the on and off states. Instead of optimizing the signal beam power, the new wavefront encoding method optimizes the ratio between the on and off states, so that, the control beam can switch the signal beam more efficiently. In addition, we can invert the wavefront switching via using different wavefront optimization targets. When the control beam is on, the signal beam can be switched to either on or off states with almost the same high extinction ratio.

2. Principle and methods

As shown in Fig. 1, a pulsed laser beam (532 nm, 7-ns pulse width) is split into a signal beam and a control beam. The signal beam is expended to cover a spatial light modulator (SLM, SLM-100, Santec Corp). A computed phase map is displayed on the SLM to change the wavefront of the signal beam. Then a lens focuses the signal beam on a

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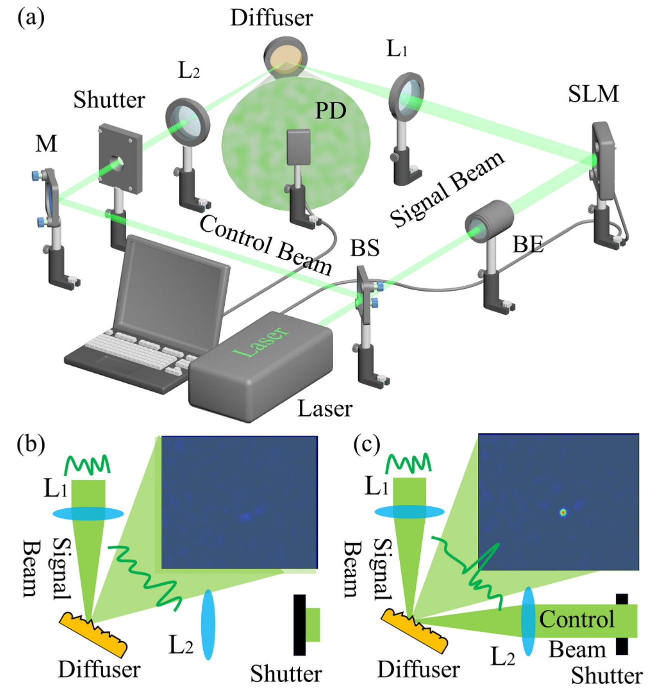

Fig. 1. (a) Experimental setup of the invertible wavefront switching system. The signal beam is reflected on a spatial light modulator (SLM) and then focused on a diffuser to generate a speckle pattern. A control beam disturbs the diffuser via thermo-optic effect. A photodiode with a pinhole measures the power of a speckle grain generated from the signal beam. The wavefront of the signal beam is optimized to enhance the extinction ratio. (b) The off state: The control beam is blocked by a shutter. (c) The on state: The control beam is on. The on and off states can be inverted via changing the wavefront on the SLM. BE: beam expander; BS: beam splitter; L: lens; M: mirror; PD: photodiode; SLM: spatial light modulator.

reflective diffuser coated with gold (DG10-120-M01, 120 grid, Thorlabs) to generate a speckle pattern. The control beam focuses on the diffuser at the same spot as the signal beam. Both the sizes of the signal and the control beam are ~50 μm in diameter. Because the control beam can change the backscattering of the diffuser by inducing thermo-optic effect and thermal induced ultrasound [15], the reflected speckle pattern of the signal beam will be different when the control beam is on or off. A photodiode (PD) with a 50-μm pinhole detects the intensity of a speckle grain at on or off states. Because the power of the control beam is stronger than the signal beam, the speckle pattern of the control beam is almost constant during the optimization process. We calibrate and remove the contribution of the control beam speckle from the PD measurement. The phase pattern on the SLM is optimized with a genetic algorithm [1,3]. The PD measurement ratio between the on and off states (V_{on}/V_{off}) is used as the optimization goal. In the off state, the V_{off} may be too low, and the ratio may become unstable due to the measurement noise. To avoid this problem, we define a modified on/off ratio as:

$$R_{eff} = V_{on\_eff}/(V_{off\_eff})^{\alpha}, \tag{1}$$

where $V_{on\_eff} = V_{on}/V_{kt}$, $V_{off\_eff} = V_{off}/V_{kt}$, and $\alpha = 1/(1 + \exp((V_{exp} - V_{off})/V_F))$. V_{kt}, V_{exp} and V_F are constant values to keep V_{off} above a minimum value. When V_{off} is much smaller than V_{exp}, the V_{off_eff} approaches 0, and α is smaller than 1. Thus the $(V_{off\_eff})^{\alpha}$ in Eq. (1) is greater than V_{off_eff}, and R_{eff} is smaller than V_{on}/V_{off}. Optimization of R_{eff} will tend to exclude the phase patterns that lead to V_{off} much smaller than V_{exp}. When V_{off} is greater than V_{exp}, the R_{eff} approximates to V_{on}/V_{off}. The genetic algorithm will select the phase patterns that increase V_{on} and decrease V_{off}. As a result, V_{off} will be maintained around V_{exp}, and V_{on} will keep increasing. In our experiments, V_{kt}, V_{exp} and V_F are set at 26 mV, 2.6 mV and 0.52 mV, respectively.

3. Results

Fig. 2(a) shows the on and off signals during the wavefront optimization based on the on signal only. The fluence of the control beam is 220 mJ/cm^2. When the control beam is on, the switch is in the on state. As we optimize the on signal, the off signal also increases. We stop the iteration when the signal increase becomes slow. The highest extinction ratio (V_{on}/V_{off}) is 2.5. We also optimize the wavefront based on the modified on/off ratio (R_{eff}). The on and off signals are shown in Fig. 2(b). The off signal remains almost the same during the optimization process, and the on signal keeps increasing. When the optimization stops, the highest extinction ratio is 16.6, ~660% of that optimizing the on signal only. The interaction area between thermal disturbance and probe beam is confined on the diffuser surface. In addition, the phase disturbance by heating the reflecting gold coating and by the thermal excited ultrasound is limited. As a result, the phase disturbance by the control beam is not very efficient in this experiment. After we optimize the on signal only, the extinction ratio is too low to show a good contrast between the on and off states during wavefront switching. Improving the disturbance efficiency may increase the extinction ratio but will bring potential damage to the reflective diffuser. We need to develop a new method to further improve the extinction ratio. Here we optimize the modified on/off ratio (R_{eff}), and the genetic algorithm chooses phase patterns that increase the on signal and hold the off signal low. As a result, the control beam can effectively switch the on and off states with a high extinction ratio. Fig. 2(c) compares the performances of two wavefront switches optimized with the on signal and the modified on/off ratio. In the experiment, the optimized phase patterns are displayed on the SLM, and the control beam controls the switch between on or off states. Both types of switches show a good repeatability.

Via using different optimization targets, we can invert the wavefront switch, i.e., when the control beam is on, the signal beam can be in either on or off states. Fig. 3(a) and (b) show the wavefront optimization processes for both non-inverted and inverted switches. The non-inverted switch, as shown in Fig. 3(a), has an extinction ratio of 19.3. The inverted switch has an extinction ratio of 18.8. The results indicate that both the non-inverted and inverted switches can be realized with a high extinction ratio. The speckle patterns on the pinhole plane are shown in Fig. 3 (c). Bright light spots can be seen in Fig. 3(c)-① and ④, corresponding to the on states of the non-inverted and inverted switches. Fig. 3(c)-② shows the speckle pattern when the non-inverted switch is off. The light spot almost disappears. Fig. 3(c)-③ shows the speckle pattern when the inverted switch is off. Although a relatively bright spot is still visible, the spot location shifts away from the pinhole location. Most energy of the signal beam is blocked by the pinhole.

Fig. 4 shows the optimized extinction ratios at different control beam energies. As the control beam fluence increases from 30 mJ/cm^2 to 220 mJ/cm^2, the extinction ratio increases from 4.4 to 18.3. The control beam energy determines the disturbance of the diffusive reflection on the diffuser. When the control beam energy exceeds 130 mJ/cm^2, evident extinction ratio over 8 is observed. When the control beam energy is lower than this value, the disturbance is inefficient, and the extinction ratio is low. Although beyond the scope of this paper, we expect that using a different phase disturbance mechanism may further improve the extinction ratio of the wavefront switch.

4. Conclusions

In conclusion, we develop an invertible wavefront switching technique via optimizing the wavefront of the signal beam. The goal of the wavefront optimization is to increase the on/off signal ratio under

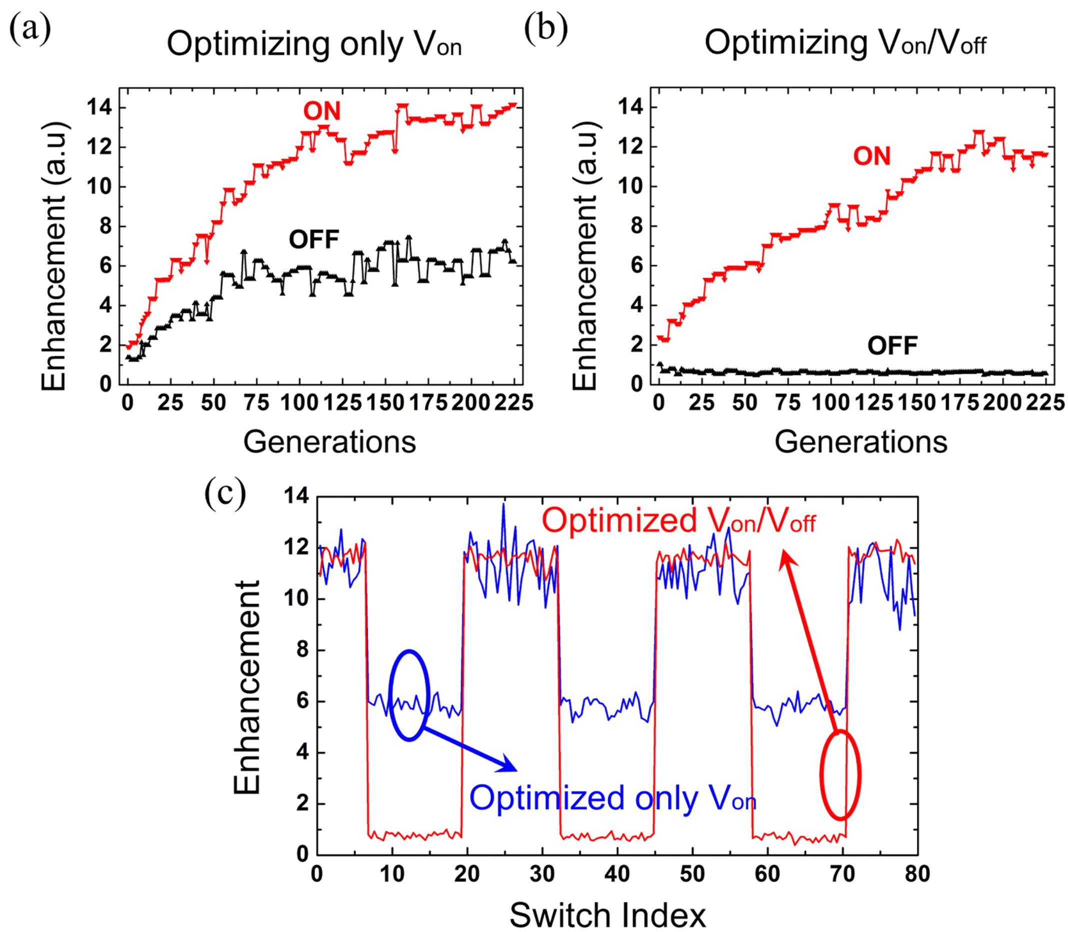

Fig. 2. Iterative optimization of a switchable wavefront encoding system. (a) The on and off signals when using only the on signal for wavefront optimization. (b) The on and off signals when using the modified on/off ratio (R_{eff}) for wavefront optimization. (c) Switching tests for the two wavefront optimization approaches in (a) and (b).

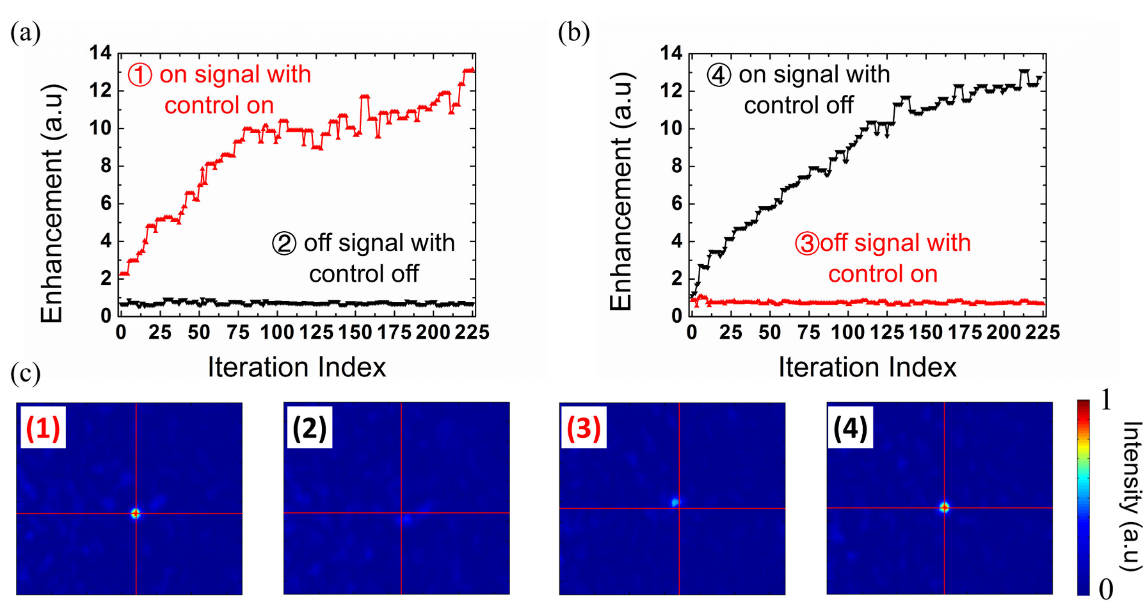

Fig. 3. Wavefront optimization for the invertible wavefront switch. (a) Optimization with the modified on/off ratio. The state is on when the control beam is on. (b) Optimization with the modified off/on ratio. The state is on when the control beam is off. (c) Speckle patterns generated from the signal beam. (1) and (2) are the on and off states corresponding to (a). (3) and (4) show the off and on states corresponding to (b).

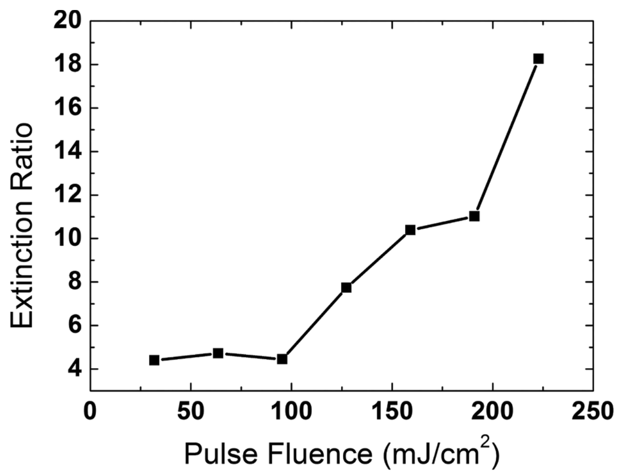

Fig. 4. Extinction ratio versus fluence of control beam for a non-inverted wavefront switch.

disturbance by a control beam. After optimization, the control beam can effectively switch the signal beam to on or off states. Experimental results show that the extinction ratio can reach ~20. This technique can be configured to either non-inverted or inverted modes, offering great flexibility. In this paper, a rough reflector is used as diffuser and the energy loss is high in current system. The rough reflector can be replaced by other elements, such as a multimode fiber for example, to improve throughout efficiency. In addition, in terms of a higher extinction ratio, a faster speed, or a lower control power may rely on the exploration of new disturbance mechanisms and new laser sources. Current disturbing mechanism is thermo-optic effect of coated gold film. The use of a ps or fs pulsed laser may induce ultrafast disturbing via different mechanisms, such as Kerr effect, ultrafast electron excitation or nonlinear absorption. In such cases, efficient all-optical switch with short switching time and low control energy may be achieved, maintaining invertible properties and high extinction ratio at the same time.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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