Double-Light-Path Multiplexing Enabled Light Shaping Efficiency Enhancement for Digital Micromirror Device

Lei Zhu[1], Zizheng Cao[2], Songnian Fu[3,*], Yuncai Wang[3], and Yuwen Qin[3]

[1]*Wuhan National Laboratory for Optoelectronics, and School of Optical and Electronic Information, Huazhong University of Science and Technology, Wuhan, 430074, China*
[2]*Institute for Photonic Integration, Department of Electrical Engineering, Eindhoven University of Technology, Eindhoven, the Netherlands*
[3]*School of Information Engineering, Guangdong University of Technology, and Guangdong Provincial Key Laboratory of Photonics Information Technology, Guangzhou, 510006, China*
*songnian@gdut.edu.cn

Abstract: In order to solve the low conversion efficiency (theoretically less than 10%) of digital micromirror device (DMD) based light shaping, we demonstrate a double-light-path multiplexing technique to double corresponding light shaping efficiency.

1. Introduction

A digital micromirror device (DMD) is a micro-electromechanical device, with millions of reflective micromirrors to switch light on/off individually [1]. Due to fast refresh rate (~kHz), high fill factor of around 90%, and wide operation wavelength range from 350 nm to 2000 nm, the DMD has been applied in lots of areas, such as digital light processing, beam steering, light shaping, wavefront correction and visible light communication. However, since it is a binary amplitude-type spatial light modulator (SLM), the efficiency of light shaping is much lower in comparison with the phase-type SLM. The theoretical efficiency limitation of light shaping is $1/\pi^2 \approx 10\%$ [2] for a binary amplitude-type SLM. On the contrary, the efficiency of phase-type SLM can reach a much higher value, even higher than 90%. Each mirror of the DMD can be independently addressed to tilt either $+12°$ or $-12°$ with respect to the surface of DMD, indicating of the "on" or "off" state for each pixel. Owing to the unique mechanical structure of the mirror, DMD can spatially modulate the amplitude distribution of incident light by deflecting the light into two different directions. In previous research and applications, the light reflected to the "off" direction is always absorbed by a heat sink, without any proper usage. In this submission, we identify that the light at the "off" path encodes the same target light field information in terms of amplitude and phase, the same as the "on" path does. Our simulation results show that via multiplexing the "on" and "off" light paths, the efficiency of light shaping can be doubled.

2. Operation principle

As shown in Fig. 1(a), when a plane wave illuminates the DMD with an angle of $24°$ with respect to the Z-axis. The mirrors of "on" state reflect the light towards Z-axis at the "on" light path. Meanwhile, the mirrors with "off" state deflect the light along the "off" path. The "on" path and "off" path are separated in space with an angle of $48°$, according to the reflection law. Generally, the light at the "off" path is absorbed by a heat sink in previous applications. Since each mirror only has two states, either 1 or 0, the amplitude mask functions toward the "on" path or "off" path are always complementary, as shown in Fig. 1(b) and (c).

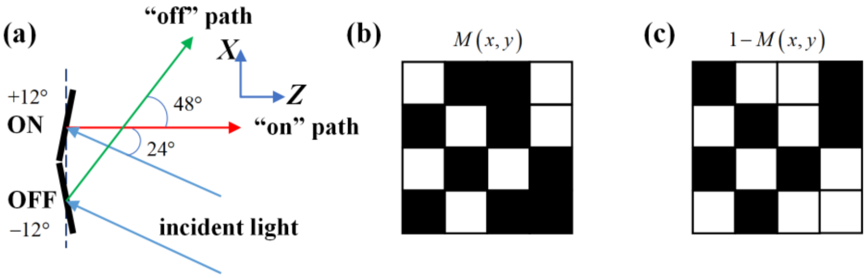

Fig. 1 (a) Mechanism of mirror binary state, and the complementary masks at the (b) "on" path and (c) "off" path.

As for the light shaping, complex-amplitude field manipulation is highly desired. Therefore, we set the target field as $E_{target}(x,y) = a(x,y)\exp[i\varphi(x,y)]$, where the amplitude $a(x,y)$ is a positive normalized function and the phase $\varphi(x,y)$ takes values from an interval of $[-\pi,\pi]$. In order to realize amplitude and phase manipulation simultaneously with the help of a binary amplitude-SLM, Lee method [3] and Super-pixel method [4] have been proposed successfully. Although the algorithm of both two methods to encode the target field information into the binary mask function $M\left(x,y\right)$ is different, the lens-based 4-f filtering system is used for both methods, for the ease to select the target field in spatial frequency domain. As a result, the mask function can be decomposed as

$$M\left(x,y\right)=ma\left(x,y\right)\exp\left\{i\left[\varphi\left(x,y\right)+2\pi\left(ux+vy\right)\right]\right\}+n\left(x,y\right), \tag{1}$$

where m is a positive scaling factor, u and v denote the spatial frequency of carrier wave in x and y direction, $n\left(x,y\right)$ is the noise. The first term in Eq. (1) is the modulated signal with a carrier wave, whose spectrum can be separated from the spectrum of noise in the Fourier plane, due to the ingenious design of binary mask. After filtering in the frequency domain to select the spectrum of first term in Eq. (1), then inverse Fourier transformation is applied to recover the signal at the output. Please note that the output of 4-f system is the first term of Eq. (1), with an undesired phase term $2\pi\left(ux+vy\right)$. Such phase term is the phase of a tilted plane wave, which will not affect the desired phase distribution of $\varphi\left(x,y\right)$ and can be easily eliminated. $M\left(x,y\right)$ is the mask function for the light at the "on" path, and similarly, the complementary mask function for the light at the "off" path can be decomposed as

$$\begin{aligned}M'\left(x,y\right)&=1-M\left(x,y\right)=1-ma\left(x,y\right)\exp\left\{i\left[\varphi\left(x,y\right)+2\pi\left(ux+vy\right)\right]\right\}-n\left(x,y\right)\\&=ma\left(x,y\right)\exp\left\{i\left[\varphi\left(x,y\right)+\pi+2\pi\left(ux+vy\right)\right]\right\}+1-n\left(x,y\right).\end{aligned} \tag{2}$$

The spectrum distribution range of $-n\left(x,y\right)$ and $n\left(x,y\right)$ in Fourier plane is identical. Moreover, the constant term of "1" in Eq. (2) is the zero-order light, which is away from the spectrum zone of spatially modulated signal because of the existence of u and v. We can find that there is only one more plane phase retard of π in the first term in comparison with the one in Eq. (1). As a result, from the complementary mask at the "off" path, the target optical filed can also be obtained. In a summary, the information encoded in two masks is identical.

3. Simulation results

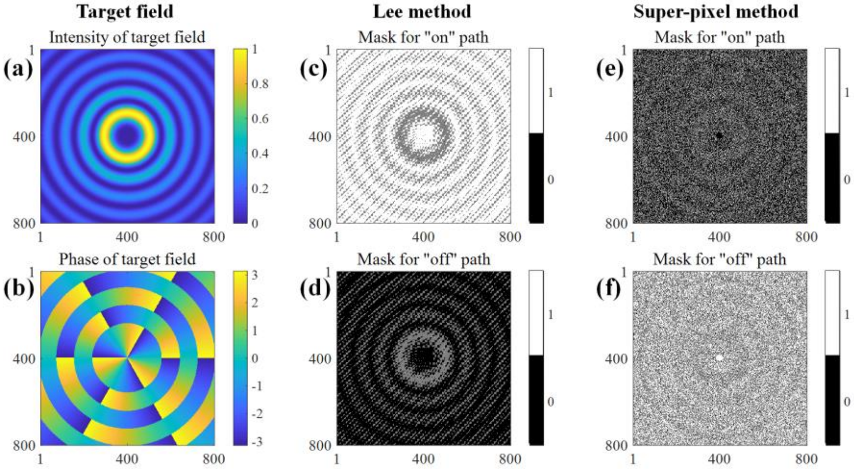

Fig. 2 Target field of 3rd-order Bessel beam and calculated binary masks on DMD for "on" path and "off" path under conditions of two methods, respectively.

By considering the 4-f based filtering system, each with two lens and a pinhole, are put along at the "on" path and "off" path to obtain desired complex optical field. A target field of 3rd-order Bessel beam is chosen, as shown in Fig. 2(a) and (b). Then the functions of binary mask are calculated by Lee method and Super-pixel method, respectively, as shown in Fig. 2(c)-(f). The 4-f filtering systems are built up by MATLAB, in order to simulate the results of the obtained field, respectively, as shown in Fig. 3. We find that the Bessel beam with 3rd-order helical phase can be successfully generated at the "on" path, by two different methods. Meanwhile, the "off" path with complementary mask have the same results. The phase distribution has a constant phase retard of π, which is consistent with the theoretical prediction by Eq. (2). In order to evaluate the quality of the generated light beam, the generation accuracy and conversion efficiency are defined. The generation accuracy is calculated by the complex fidelity, as shown in Eq. (3),

$$F = \left| \frac{\int E_{target} E^{*}_{obtained} \, dxdy}{\sqrt{\int \left| E_{target} \right|^{2} dxdy \times \int \left| E_{obtained} \right|^{2} dxdy}} \right|^{2}, \tag{3}$$

and the corresponding conversion efficiency is

$$P = \frac{\int \left| E_{obtained} \right|^{2} dxdy}{\int \left| E_{in} \right|^{2} dxdy}. \tag{4}$$

Where E_{target} and E_{obtained} denote the target filed and simulated output filed, respectively, and E_{in} is the input light field, which is regarded as a plane wave here. The quality comparison results are shown as Table 1. We can find that the efficiency is fairly low. As for the particular method, the quality of two paths is totally same. Therefore, after numerical simulation, we verify that the light at the “off” path can be also used and the same light beam can be obtained. The conversion efficiency can be doubled if both “on” path and “off” path can be spatially multiplexed.

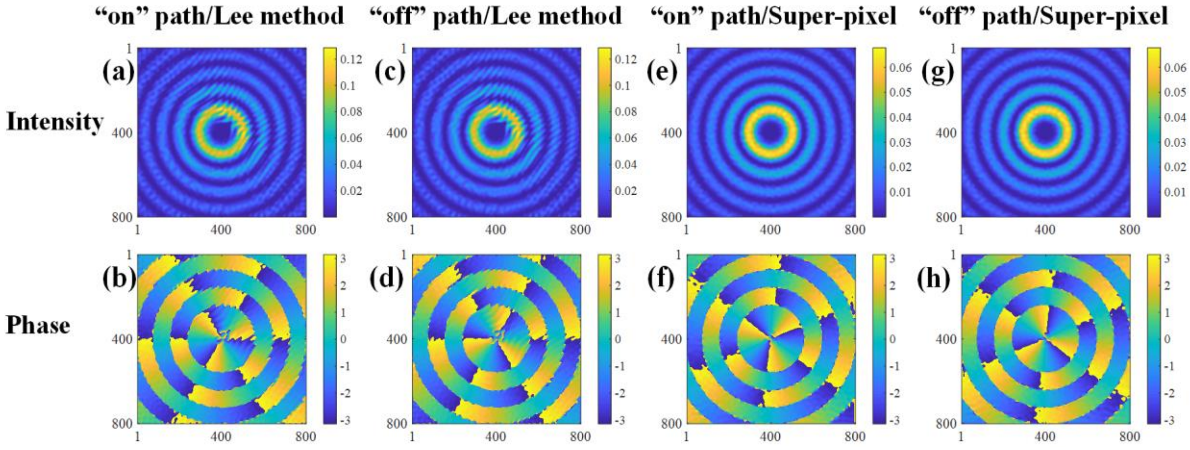

Fig. 3 Simulation results of “on” and “off” paths with two different methods.

Table 1. Quality comparison of generated beam in two paths

		Lee	Super-pixel
accuracy	“on” path	97.54%	99.38%
	“off” path	97.54%	99.38%
efficiency	“on” path	1.9%	1.14%
	“off” path	1.9%	1.14%

4. Conclusion

The binary state of micromirror arising in DMD reflects light toward two directions, which generates two complementary binary mask functions. We theoretically find that the light field information encoded with two masks is same during the application of light shaping. The simulation based on Lee method and Super-pixel method, is carried out to verify the double-light-path multiplexing enabled light shaping efficiency enhancement. By spatially multiplexing two light paths, the conversion efficiency of light shaping can be doubled. We believe that the scheme of double-light-path multiplexing is suitable for lots of DMD based applications.

5. References

[1] Y. X. Ren, R. D. Lu, and L. Gong, “Tailoring light with a digital micromirror device,” Ann. Phys. **527**, 447-470 (2015).
[2] B. R. Brown, and A. W. Lohmann, “Computer-generated binary holograms,” IBM J. Res. Dev. **13**, 160-168 (1969).
[3] W. H. Lee, “Binary computer-generated holograms,” Appl. Opt. **18**, 3661-3669 (1979).
[4] S. A. Goorden, J. Bertolotti, and A. P. Mosk, "Superpixel-based spatial amplitude and phase modulation using a digital micromirror device," Opt. Express 22, 17999-18009 (2014).