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Method to enhance the single mode fiber coupling efficiency for obscured receiver by beam shaping

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Abstract

Since the aperture obstruction contributes to an energy leak from the core to the sidelobe of the far field spot, the Gaussian mode of the single-mode fiber (SMF) will receive less energy leading to the coupling efficiency (CE) degradation. A method based on diffraction optical element (DOE) and wavefront corrector is introduced to reshape the plane wave with hollow uniform intensity into the plane wave with uniform intensity to improve the core energy of spot. The SMF CE with and without DOE for different central obscuration ratio ε is studied by numerical simulation. The DOE is effective to improve the SMF CE. Without the DOE, the CE $\langle\eta\rangle$ decreases from 81% to 54% when the central obscuration ratio ε increases from 0 to 0.4. Compared with 54% CE at the ε of 0.4, the CE $\langle\eta\rangle$ can increase to 72%, 78% and 80% with 4 level, 8 level and 16 level quantized DOE, respectively. It is not necessary to use the DOE beam shaper when the central obscuration ratio ε is small. The 4 level, 8 level and 16 level quantized DOE can obtain benefits of the CE when the central obscuration ratio ε is above 21.6%, 11.5% and 7%, respectively.

Keywords: aperture obstruction, single-mode fiber, coupling efficiency, beam shaping

(Some figures may appear in colour only in the online journal)

1. Introduction

Fiber-optic communication components, such as erbium-doped fiber amplifier and fiber modem are widely used in the free-space optical communication because of the mutual technology and reasonable cost [1, 2]. It is important to achieve maximum fiber-coupling efficiency (CE) for obtaining high signal-to-noise ratio. The fiber-CE degradation factors include angular jitter and high order wavefront distortion. A host of research has focused on the enhancement of the SMF CE. Lin *et al* have illustrated the enhancement of CE regarding the fabrication and characterization of the specific SMF [3, 4]. Toyoshima [5] and Ma [6] have developed an analytical model for the fiber-CE in the presence of angular jitter, which might be applicable to systems in the presence of weak atmospheric turbulence condition or inter-satellite communication. Adaptive optics (AO) is used to compensate the high order turbulence-induced wavefront distortion. The AO system applied in the laser communications relay demonstration project is responsible for compensating the downlink beam for atmospheric turbulence. It aims to obtain 55% CE at 20° elevation [7, 8]. Chen *et al* have studied the infuence of atmospheric turbulence conditions on SMF CE, and demonstrated an increase in the average SMF CE with AO under a relatively strong turbulence [9].

Besides issues of the low and high order wavefront distortion, the aperture obscuration also seriously degrades the fiber CE. Generally, a Schmidt–Cassegrain telescope with

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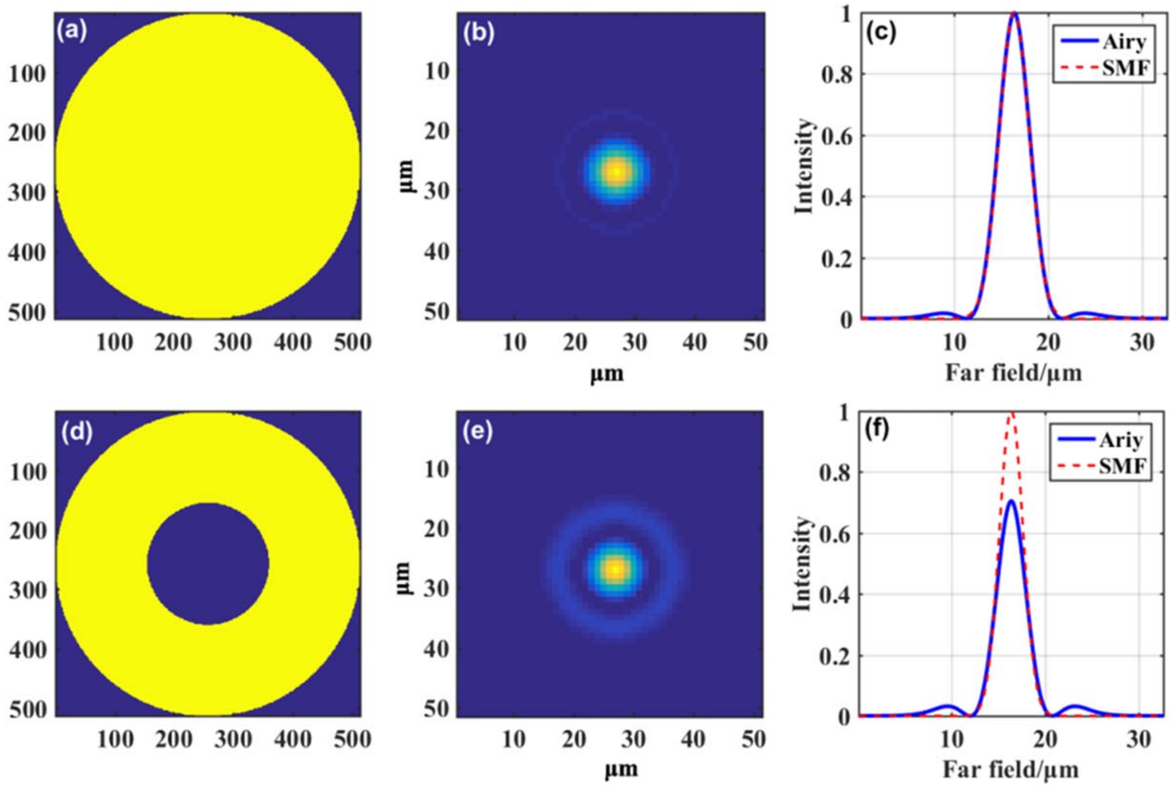

Figure 1. The pattern matching between SMF mode and different obstructed pupil focused Airy spot. (a) Near-field of unobstructed pupil; (b) far-field of unobstructed pupil; (c) lateral section of (b); (d) near-field of obstructed pupil; (e) far-field of obstructed pupil; (f) lateral section of (e).

an aperture obstruction induced by the secondary mirror is often used as the optical receiver due to its compact design [10, 11]. Since the aperture obstruction contributes to an energy leak from the central part to the side-lobes of the spot, the SMF fundamental mode will receive less energy which degrades the CE. Chunyi Chen *et al* derived an analytical solution for the fiber-CE when a plane wave is received by an annular-aperture receiver and coupled into a single-mode fiber [12]. Different approaches such as two DOEs technique [13] and two-mirror apodization technique [14] have been proposed to avoid the secondary mirror obscuration. In both cases, the two optics elements need precisely alignment to minimize phase distortion, and these studies don't focus on the enhancement of SMF CE.

In this paper, a method to enhance the SMF CE of obstructed pupil for free space laser communication is presented. To prevent energy leak from the core to the sidelobe of the spot, a DOE and a wavefront corrector are introduced to reshape the plane wave with hollow uniform intensity (HUI) into the plane wave with uniform intensity (UI). The effectiveness of the method is analyzed by numerical simulation.

2. Effect of aperture obscuration on SMF CE

The fiber CE is defined as the ratio of the average power coupled into the fiber to the average power at the pupil plane.

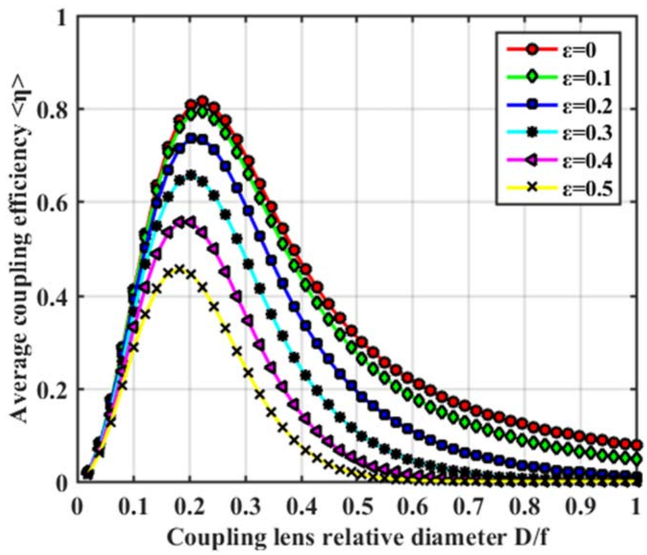

Figure 2. $\langle\eta\rangle$–D/f curves for different ε.

The theoretical value is proportional to the overlap integral of the optical field $E_A(r_a)$ and the fiber mode profile $F_A(r_a)$ at the pupil plane [15], and is given by:

$$\eta = \frac{\left|\iint E_A^*(r_a)F_A(r_a)\mathrm{d}s\right|^2}{\iint |E_A(r_a)|^2\mathrm{d}s \iint |F_A(r_a)|^2\mathrm{d}s}, \tag{1}$$

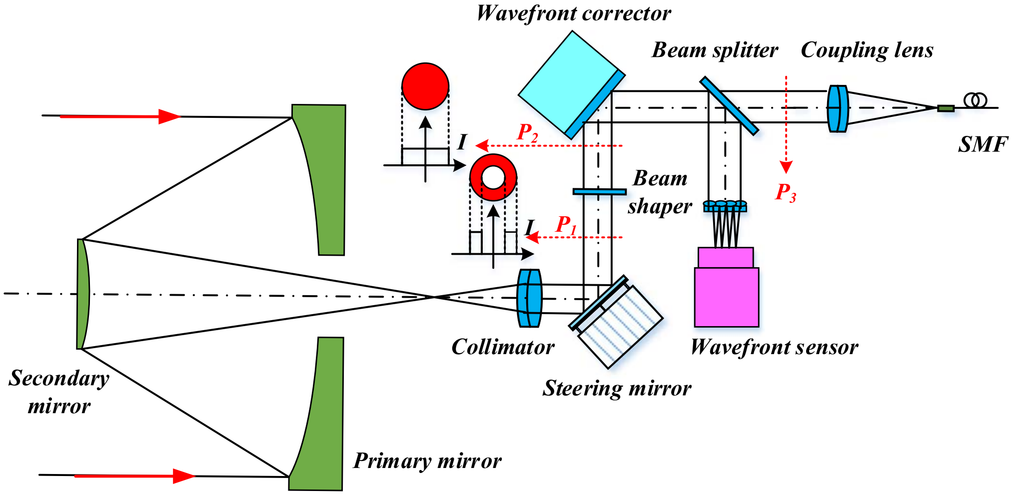

Figure 3. The beam shaping configuration of the obstructed aperture.

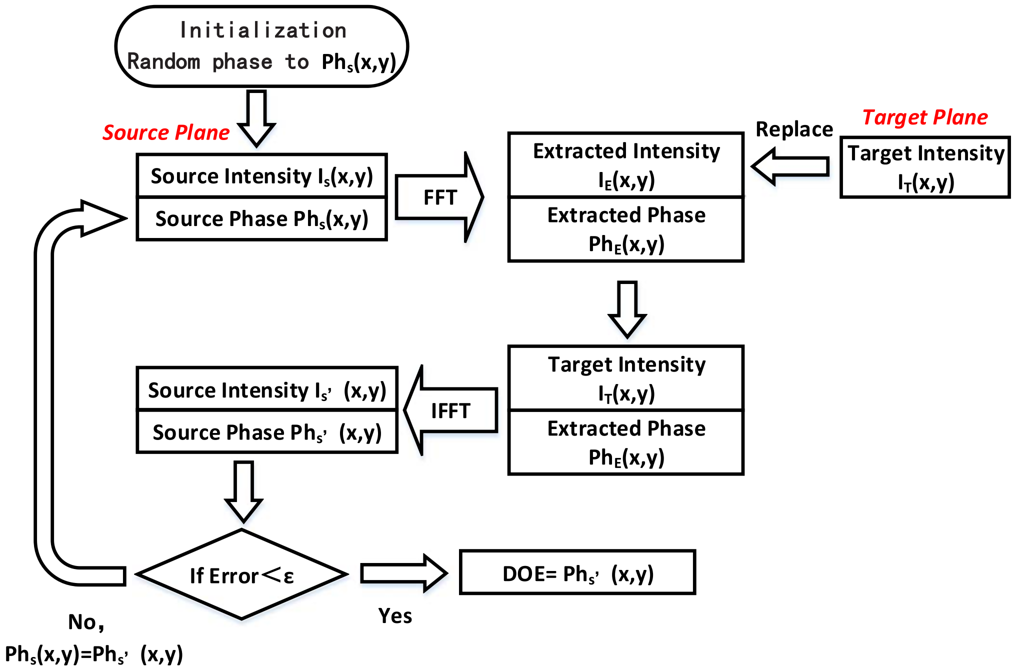

Figure 4. The IFTA algorithms for DOE design.

$E_A(r_a)$ is the incident optical field expressed as $E_A(r_a) = P_A(r_a)A(r_a)\exp(\mathrm{i}\varphi(r_a))$.

Where $P_A(r_a)$ is aperture function. $A(r_a)$ and $\varphi(r_a)$ are the amplitude and phase of the incident optical field, respectively. When the telescope with secondary mirror is used as receiver, the aperture function $P_A(r_a)$ is given by:

$$P_A(r_a) = \begin{cases} 1, \ \varepsilon \leqslant \dfrac{2|r_a|}{D} \leqslant 1 \\ 0, \ \text{otherwise} \end{cases}, \tag{2}$$

where ε is the telescope central obscuration defined by the ratio of primary mirror radius and secondary mirror radius. D is the pupil plane diameter.

$F_A(r_a)$ is the SMF fundamental mode at the pupil plane. It has a Gaussian intensity distribution and a flat wavefront expressed as:

$$F_A(r_a) = \sqrt{\frac{2}{\pi w_a^2}}\,\mathrm{e}^{-\frac{r_a^2}{w_a^2}}, \tag{3}$$

where w_a is the mode field radius of the back-propagated SMF mode given by $w_a = \lambda f/\pi w_0$, in which λ is the wavelength, f is the focal length of the coupling lens, and w_0 represents the waist radius.

When the incident optical $E_A(r_a)$ is ideal plane wave, the CE is calculated from equations (1) and (3) with the help of equation (2), leading to:

$$\eta = 2\left[\frac{\mathrm{e}^{-\varepsilon^2\beta^2} - \mathrm{e}^{-\beta^2}}{\beta\sqrt{1-\varepsilon^2}}\right]^2, \tag{4}$$

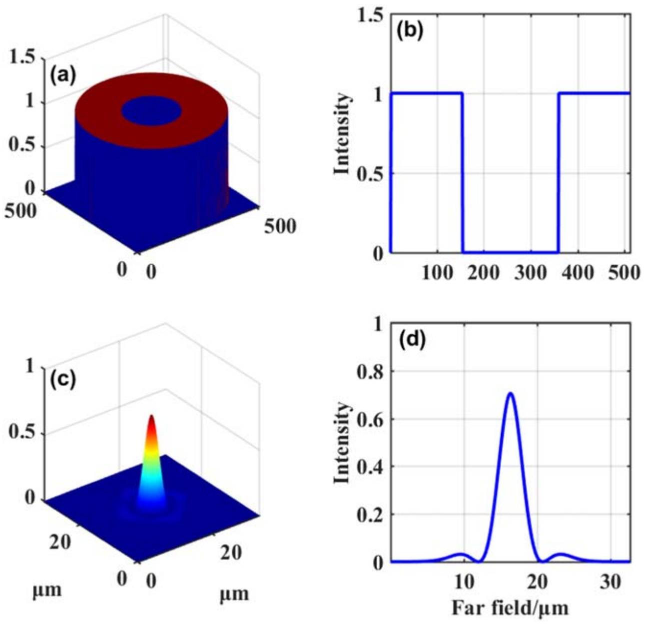

Figure 5. The HUI distribution beam at the P_1 plane. (a) Near-field of HUI beam; (b) lateral section of (a); (c) far-field of HUI beam; (d) lateral section of (c).

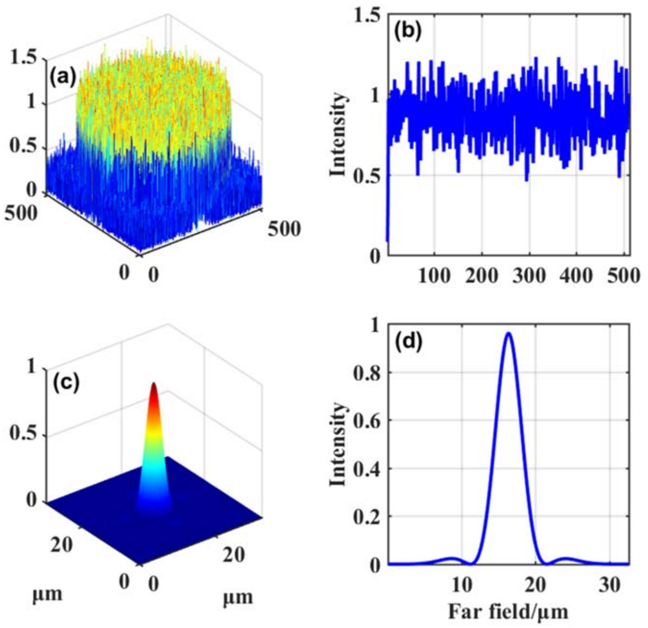

Figure 6. The shaped UI distribution beam at the P_2 plane. (a) Near-field of UI beam; (b) lateral section of (a); (c) far-field of UI beam; (d) lateral section of (c).

where $\beta = \frac{\pi D w_0}{2\lambda f}$.

As illustrated in the figures 1(a)–(c), the SMF CE is regarded as a pattern matching between SMF fundamental mode and incident light beam focused Airy spot. An unobstructed pupil ($\varepsilon = 0$) will obtain high CE of 81% for its Airy spot match SMF fundamental mode perfectly. As illustrated in the figures 1(d)–(f), Since the pupil central obscuration ($\varepsilon = 0.4$) contributes to an energy leak from the central part to the side-lobes of the spot, the fundamental mode will receive less energy which degrades the CE.

As illustrated in the figure 2, we define the wavelength $\lambda = 1550$ nm and $w_0 = 5\ \mu$m. A series $\langle\eta\rangle$–D/f curves for different ε are obtained according to equation (4). The optimized coupling lens parameter D/f helps to reach the maximum CE. The optimized D/f decreases as the increase of the ε. For example, the optimized D/f is 0.22, 0.20 and 0.18 when the ε is 0, 0.3 and 0.5, respectively. The maximum CE $\langle\eta\rangle$ at the optimized D/f decreases as the increase of the ε.

3. Method to enhance the SMF CE of obstructed aperture

As shown in the figure 3, the HUI profile generated at the P_1 plane for the obstruction of the secondary mirror will degrade the SMF CE. A method based on a beam shaper of DOE is introduced to reshape the HUI distribution beam at the P_1 plane into UI distribution beam at the P_2 plane to improve the core energy of spot. The wavefront is distorted because of DOE or atmospheric turbulence. A wavefront sensor is used to detect the beam phase distortion, and then the beam will be corrected to plane wave at the P_3 plane by wavefront corrector. The wavefront correction can be performed by suitable liquid crystal light modulators or MEM deformable mirror.

The DOE is designed using the iterative Fourier transform algorithm (IFTA) method which algorithm is given in the figure 4. The idea of the IFTA algorithms is to use known input information at the source plane (SP) and calculate the phase of a DOE that will generate a desired intensity pattern at the target plane (TP). Here, the source intensity $I_S(x, y)$ is HUI profile, and the target intensity $I_T(x, y)$ is UI profile. A random phase is assigned to the source phase $\mathrm{Ph}_s(x, y)$ during initialization, while the intensity $I_S(x, y)$ is HUI. This phase-intensity profile is Fourier transformed, and the corresponding phase values are extracted. The extracted phase $I_E(x, y)$ values are replaced by the corresponding locations of the necessary target intensity profile $I_T(x, y)$, and its inverse Fourier transform is calculated. The resulting phase profile replaces the phase profile at the SP. This is one iteration. When the iteration stopps on the condition (5), the results of $\mathrm{Ph}_s'(x, y)$ is the DOE phase.

The phase mapping of two planes evolves through the iterations until it reaches a constant value or stopped on the condition:

$$\mathrm{Error} = \frac{\int_{\mathrm{SP}} |I_{s'}(x, y) - I_T(x, y)|^2 \mathrm{d}x\mathrm{d}y}{\int_{\mathrm{SP}} |I_T(x, y)|^2 \mathrm{d}x\mathrm{d}y} < \varepsilon, \qquad (5)$$

where the ε is an infinitesimal.

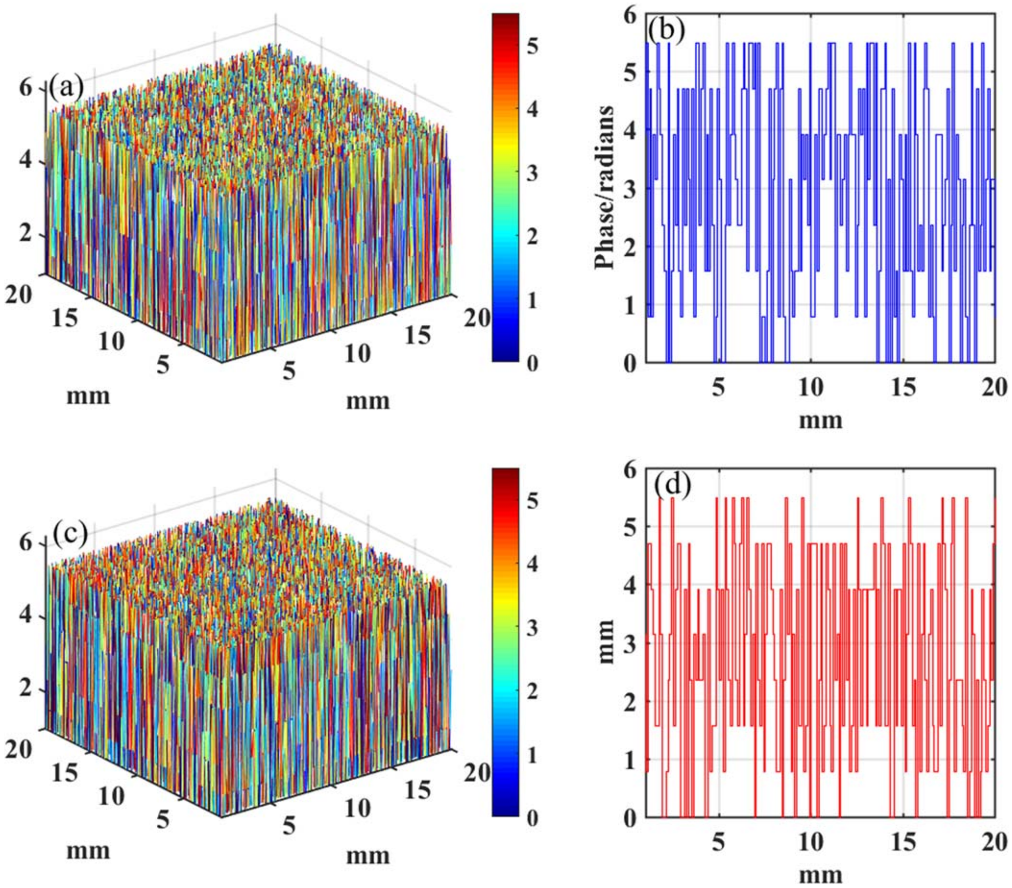

Figure 7. The phase profiles of the DOE and the wavefront corrector. (a) DOE phase profile; (b) lateral section of (a); (c) wavefront corrector phase profile; (d) lateral section of (c).

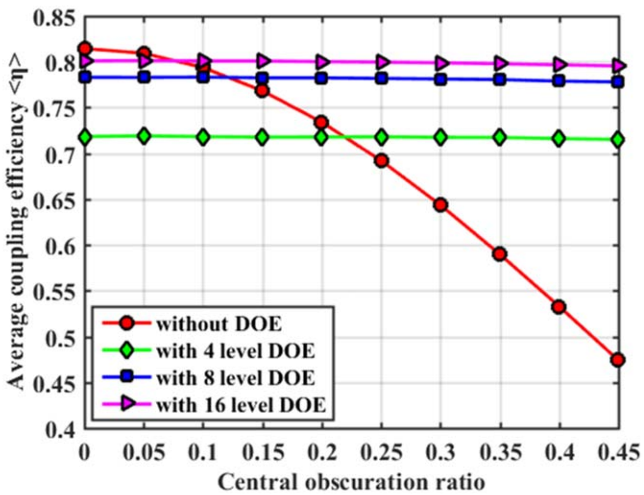

Figure 8. The SMF coupling efficiency with and without DOE for different ε.

4. Simulation the performance of the SMF CE by beam shaping

The benefits of beam shaping by DOE are investigated by numerical simulation. The parameters are defined as: wavelength $\lambda = 1550$ nm ; $\varepsilon = 0.4$; aperture diameter $D = 20$ mm. As illustrated in the figures 5(a) and (b), the received optical beam at the P_1 plane is approximated as plane wave with HUI distribution for the long-distance communication links. Figures 5(c) and (d) shows the diffraction pattern of HUI beam by using coupling lens which optimized D/f is 0.19 according to analysis results of figure 2. The diffraction efficiency inside the primary dark ring is 61.4%.

As illustrated in the figures 6(a) and (b), the HUI profile beam is reshaped to UI profile at the P_2 plane by using a 8 level quantized DOE. The energy is normalized by the total energy at the P_1 plane during the transformation. Afterwards, the UI beam's phase is transformed into plane wave at the plane P_3 by using wavefront corrector. Figures 6(c) and (d) shows the far field pattern of UI beam with plane wave phase by using coupling lens which optimized D/f is 0.22. The diffraction efficiency inside the primary dark ring is 81.9%.

Figure 7 shows the phase profiles of the DOE and the wavefront corrector, which represent an arbitrary radial distribution. The DOE phase has been quantized by 8 level. When the silica glass with diameter 20 mm is used as the DOE substrate. The DOE profile maximum depth $d_{\max}$ is calculated by $d_{\max} = \lambda(g-1)/(g(N-1))$, where λ is the wavelength, g is the number of phase levels, and N is the substrate refraction index. Here, $\lambda = 1.55\ \mu$m, $N = 1.44$, and $g = 8$. It gives the $d_{\max}$ is 3.08 μm. The height of phase step is 0.44 μm, and the step size is 100 μm $\times$ 100 μm. Precision laser-writing systems are commonly used for fabrication of

DOE. These systems can manufacture continuous-relief and binary microstructures with minimum feature sizes of less than 0.6 μm and laser beam positioning accuracy of 0.05 μm over 300 mm substrates [16].

The SMF CE with and without DOE for different central obscuration ratio ε is shown in figure 8. Some parameters are defined as: wavelength $\lambda = 1550$ nm , $w_0 = 5\ \mu$m and $\varepsilon = 0$–0.45. Without the DOE, the CE $\langle\eta\rangle$ decreases as the increase of the ε. The $\langle\eta\rangle$ is 81%, 73.5% and 54% when the ε is 0, 0.2 and 0.4, respectively. The CE $\langle\eta\rangle$ can be increased to 72%, 78% and 80% when the 4 level, 8 level and 16 level DOE is used as beam shaper, respectively. With the DOE, the CE $\langle\eta\rangle$ decreases slightly as the increase of the ε. The High level quantization of DOE is help to obtain high CE, but it is not convenience for manufacturing. It is not necessary to use the DOE beam shaper when the central obscuration ratio ε is small. The 4 level, 8 level and 16 level quantized DOE can obtain benefits of the CE when the central obscuration ratio ε is above 21.6%, 11.5% and 7%, respectively.

5. Conclusion

A method to enhance the SMF CE of obstructed pupil for free space laser communication was presented in this paper. DOE and wavefront corrector was introduced to reshape the plane wave with HUI into the plane wave with UI to improve the core energy of spot. The SMF CE with and without DOE for varying central obscuration ratio ε was analyzed.

(1) The results show that the DOE beam shaper is useful for improving the SMF CE. When the central obscuration ratio ε increases from 0 to 0.4, the CE $\langle\eta\rangle$ decreases from 81% to 54% without DOE beam shaper. In comparison, the CE $\langle\eta\rangle$ of $\varepsilon = 0.4$ can increase from 54% to 72%, 78% and 80% with 4 level, 8 level and 16 level quantized DOE, respectively.

(2) The DOE beam shaper is not necessary when the central obscuration ratio ε is small. The 4 level, 8 level and 16 level quantized DOE can achieve CE benefits when the central obscuration ratio ε is above 21.6%, 11.5% and 7%, respectively.

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