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The new design of tapered fiber array for space optical receiver

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ABSTRACT

The coupling of space light to optical fiber is the key problem in free space optical communication. The diameter of fiber core is very small, which brings great difficulty to coupling. We first analyze the coupling model, and propose the conical fiber array as a new receiver to improve the efficiency. After that, the sample of conical fiber array is produced in the laboratory, and the testing experiment in micro vibration environment is carried out. In this experiment, two methods are used to measure the received optical power. In the first method, the light from nine fibers is merged into one with the optical splitter. In the second method, a large target avalanche photodiode (APD) is used to receive the light from nine fibers. Compared with our previous work, both measurement methods show the coupling efficiency of the conical fiber array is higher.

1. Introduction

Due to the advantages such as informative, safe and reliable etc., free space optical communication attracts more and more attention. With the rapid development of optical fiber communication, the integration of the two has become a new technology. For the integration, the coupling of space light to optical fiber is a core issue. Many researchers have done a lot of research on it. A large number of literature could be found [1–3]. For example, in literature [2], based on the Rytov approximation theory, the transmission model of an orbital angular momentum (OAM) in weak anisotropic turbulence is established. In Ref. [3], a new method is proposed for determining the mode coupling coefficient in graded index multimode optical fibers. In our previous works, we have proposed the conical fiber receiver to improve coupling efficiency and have studied its features from various perspectives [4–7]. Specifically, literature [4] analyses the influence of offset on spatial light coupling. Literature [5] analyses the coupling characteristics of the conical receiver. Literature [6] analyses the bit error rate of a conical receiver. Literature [7] analyses its power distribution characteristics. Generally speaking, in these researches, the single optical fiber is used as the receiving device. The coupling difficulty lies in the small receiving area of the single optical fiber. Adopting several fibers as receiver is a new way. The multi-fibers are equivalent to several single-fiber-receivers.

At present, many literature about multi-fibers could be found. For example, in literature [8], low-cross talk and low-loss multi-core fiber is designed. In literature [9], it analyzed the photon stability in two-dimensional optical fiber arrays. In literature [10], it deduced the coupling model in the weld joint from single fiber to double fibers. On the whole, these literature discuss cylindrical fiber. In this work, we propose the multi-conical-fiber as the receiver. In this new design, multi-conical-fiber could expand the receiving area to improve the coupling efficiency.

2. The coupling model of space light to fiber

2.1. The mathematical coupling model of space light to single fiber

As shown in Fig. 1, when the light is coupled into the fiber through the grin lens, the light trace (on the incident plane of the lens $z = 0$, initial position is x_0) meets the following equation [11–13].

$$\begin{cases} x = x_0 \cos(\sqrt{A} z) \\ P = -x_0 \sqrt{A} \sin(\sqrt{A} z) \end{cases} \tag{1}$$

Where P is the slope of the light; A is the focusing constant. If $z = P/4 = \pi/(2\sqrt{A})$, the parallel light will be converged to the focal point. We assume the numerical aperture of fiber is d_{NA}. When $\sin(90^0 - \arctan P) \le d_{NA}$, namely $x_{\max} < |\cot(\arcsin d_{NA})/\sqrt{A}|$, the space light can be coupled into the fiber. $x_{\max}$ is the effective coupling radius.

As shown in Fig. 1, the light has 3 mutation positions (labeled as 1, 2, 3 in the figure). Due to the influence of the factors such as reflectivity mutation, lens aberration etc., the coupling efficiency will decreases. We set it as η_s. Then, the coupling efficiency of spatial light-to-fiber could be looked as the gate function of η_s [14,15].

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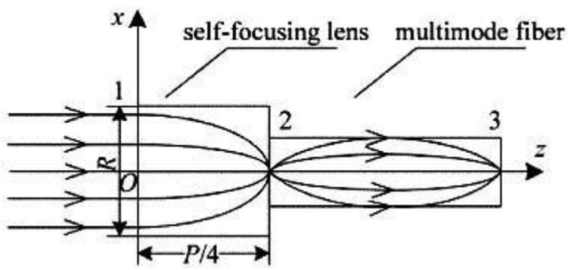

Fig. 1. Coupling model of space light into fiber. 2, 2 The efficiency numerical calculation of conical fiber array.

$$\alpha_s(x) = \begin{cases} \eta_s, & (-x_{\max} \le x \le x_{\max}) \\ 0, & (x < -x_{\max},\ x > x_{\max}) \end{cases} \tag{2}$$

For the fiber array coupling system, when the light of incidence is vertical to the plane of optic axis, the light intensity belongs to Gauss distribution [16,17].

$$I(x) = \exp[-2(x/\omega_0)^2] \tag{3}$$

Where ω_0 is the radius of the Gauss field; x is the distance between the beam and the center of the coupling surface. In order to make the calculation simplified, we only consider the displacement in X axis direction, the attenuation function of array $\alpha(x)$ could be expressed as the following equation.

$$\alpha_s(x) = \begin{cases} \alpha_s(x + x_f), & (-1.5x_f \le x < 0.5x_f) \\ \alpha_s(x), & (-0.5x_f \le x \le 0.5x_f \\ \alpha_s(x - x_f), & (0.5x_f < x \le 1.5x_f \\ 0, & (x < -1.5x_f, \quad x > 1.5x_f) \end{cases} \tag{4}$$

Where, x_f is the distance between two adjacent fibers, as shown in Fig. 2.

Fig. 2 is the schematic diagram of 3 × 3 fiber array. In order to make the calculation simplified, we only consider the situation that the incident light spot moves in the direction of X axis. Then, the light intensity which is coupled into the optical fiber $I_{in}(x)$ is equal to the convolution between the light intensity at the lens surface $I(x)$ and the attenuation function $\alpha(x)$ [17–19].

$$I_{in}(x) = I(x) * \alpha(x) \tag{5}$$

Then, the coupling efficiency of array $\eta(x)$,

$$\eta(x) = \frac{I_{in}(x)}{I_{sum}(x)} = \frac{I_{in}(x)}{\int I(x)dx} \tag{6}$$

To assume the focused spot radius of the incident light is 25 μm, the radius of the single tapered fiber is 25 μm, NA is 0.21, wavelength is 850 nm, light quality factor M^2 is 1, the coupling efficiency of single ordinary fiber is 60% (the data is from practical measurement). For the single tapered fiber, compared with ordinary single fiber, its coupling efficiency falls by 10% (the data is from previous related research [4–7]). To ignore the influence of conical fiber on transmission mode, according to the above formulas from 1 to 6, with the numerical analysis method, the coupling efficiency of tapered fiber array can be calculated out, which is shown in Fig. 3.

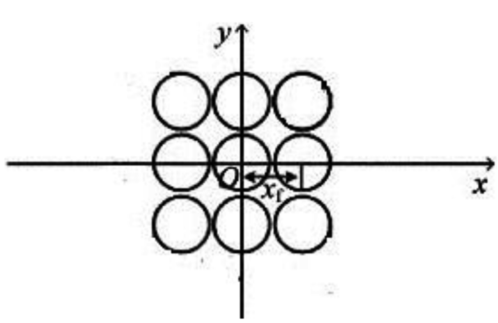

Fig. 2. The distance of x_f in the conical fiber array.

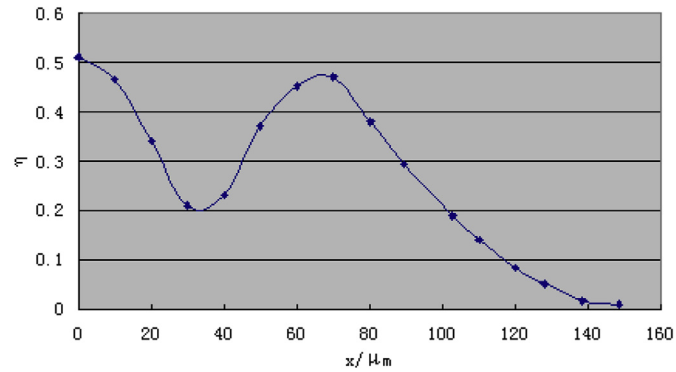

Fig. 3. Coupling efficiency of conical fiber array.

As shown in Fig. 3, x is the distance between the center of the fiber array and the center of the light spot. When x is increasing from 0 to 25 μm, the coupling efficiency is decreasing gradually from 52% to 20%. When x is increasing continuously from 25 μm to 75 μm, the coupling efficiency is increasing gradually from 20% to 48%. When x is increasing continuously from 75 μm to 150 μm, the coupling efficiency is decreasing all along.

In Fig. 3 above, we only consider the displacement in X axis direction. If we exploit the different geometry of the array (both in terms of radii of the receiver fibers and also in term of geometrical arrangement of them in the array) to eventually improve the coupling efficiency, it would be better. But due to the restrictions of time and effort, we did not do this work at this time. In future, we intend to do it.

3. The experiment test

3.1. The fabrication of the new conical fiber array

In order to study the performance of the conical fiber array, the author had a discussion with the technicians of ChengDu ZhongZu Optical Fiber Co., Ltd. A sample of new tapered fiber array was produced in the company's technology research department. And the experimental test was carried out.

In order to produce the conical fiber array, firstly, the conical fibers are produced one by one. After nine tapered fibers are prepared, they are arranged in order and adhered with the binding to form the sample of the conical fiber array.

In the process of the single conical fiber production, we adopt the fused biconical taper technology to reform the large diameter fiber (its diameter is about 75 μm). At present, with the development of optical communication, this technology becomes more and more advanced. In this experiment, SCS-4000 fused tapered system is used to make the biconical tapered fiber. Firstly, the fiber is fixed on the pull plate and its middle is heated. Then, the pull plate is dragged by the controlled system. In the proper control strategy, we get the double cone structure, which is shown in Fig. 4 (A). Then, we cut it with a precision optical

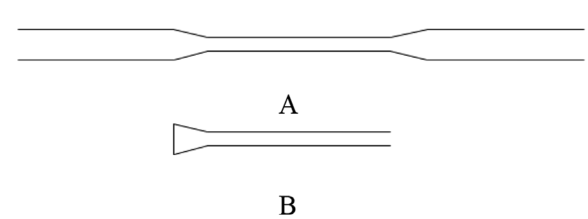

Fig. 4. The process of making a conical fiber.