Optics Communications 394 (2017) 18–22

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

The spatial light receiver and its coupling characteristics☆,☆☆

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A R T I C L E I N F O

Keywords:
Optical fiber connector
Coupling efficiency
The free space optical communication
Tapered structure

A B S T R A C T

The effective couple of the space light into the optical fiber is the key point of the free-space optical communication. In order to solve this problem, the novel tapered optical fiber head is proposed. The special tapered structure could improve coupling efficiency through expanding the light receiving area. In order to study its coupling characteristics, the longitudinal propagation constant of the connector is expanded by Taylor series according to the wave theory. And the approximate solution of the power distribution is obtained. Then, the coupling efficiency measurement experiment with the tapered connectors and the conmmon connector is finished. The experimental result is consistent with the theoretical analysis basically. This work provides a theoretical reference for the design of the new tapered connector, which could be adopted in the free-space optical communication.

1. Introduction

As a new communication technology, free-space optical communication has broad application prospects. Through the common optical fiber communication technology is becoming more and more widely used and reliable, the combination of the two is a recognized trend. The effective couple of the space light into the optical fiber is the key problem of the combination.

In order to solve this key problem, A lot of related studies and achievements could been found at home and abroad [1–7]. In the reference [1–3], the expression of the average coupling efficiency of the spacial light to single-mode fiber was calculated based on the cross-correlation function of the incident light field. In the reference [4–6], the research on the characteristics of adaptive optics compensation to improve the efficiency of fiber coupling under turbulent flow conditions has been done. In the reference [7], the probability of the coupling efficiency of the optical fiber is given based on the numerical simulation method.

On the whole, most of those studies focous on the coupling of the spacial light to the cylindrical optical fiber. The literatures about the coupling of the spacial light to the tapered fiber connector are quite few. On the other hand, the tapered optical fibers have been utilized for diverse applications, especially in the sensor, photonics and quantum optics. For example, ALVARO FZ [8] has analyzed the availability and cost of PONs based on a network geometric model. YANG Hai etal. [9] has studied the transmission of polarized light of space atticude in quantum communication. Shan Zhu et al. introduced the atomic layer deposition technology to fabricate a high sensitivity RI sensor based on an adiabatic tapered optical fiber, where an asymmetric Fabry-Perot like interferometer is constructed along the fiber taper [10]. Peter Tatar et al. proposed a modification structure model of in-fiber sensor based on intermodal interference in two core photonic crystal fibers for measuring external RI [11].

At the same time, the fused tapered method is widely studied. For eaxmple, Le Xu et al. proposed a high-temperature sensor based on an abrupt fiber-taper Michelson interferometer in single-mode fiber (SMF) fabricated by a fiber-taper machine and electric-arc discharge [12]. S. A. Ibrahim et al. proposed an ammonia sensor composed of a tapered multimode fiber coated with polyaniline nanofibers, and Fu Guangwei et al. analyzed crystal fiber Mach-Zehnder interferometer (MZI) based on CO_2 laser fusion technology [13,14].

In this paper, the tapered optical fiber is proposed to be adopted in the coupling of the spacial light to the fiber. The special tapered structure could improve coupling efficiency through expanding the light receiving area. In order to study its coupling characteristics, the longitudinal propagation constant of the connector is expanded by Taylor series according to the wave theory. And the approximate solution of the power distribution is obtained. Then, some parameters'

☆☆ Note: Project has been authorized Chinese Patent, the name of the patent: “The directional optical fiber with tapered plug”; patent application number: CN201620005088.0; public/notice number: CN205301623U.

☆ Project supported by the National Natural Science Foundation of China (Grant no. 61275080), the National Technology Innovation Fund (Grant no.13C26212201166).

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http://dx.doi.org/10.1016/j.optcom.2017.02.067
Received 16 December 2016; Received in revised form 18 January 2017; Accepted 28 February 2017
Available online 06 March 2017
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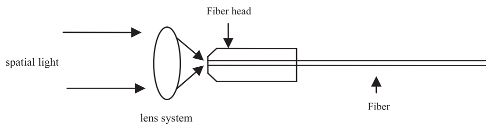

Fig. 1. The conmmon coupling system of spatial light to optical fiber.

influence on the coupling efficiency are discussed, such as taper length, fiber refractive index etc. After that, the test measurement experiment is done, whose result is consistent with the previous theoretical analysis. The work provides a theoretical reference for the design of the new tapered connector, which could be adopted in the space optical coupling system.

2. The traditional optical fiber coupling system and new coupling model

Shown as in Fig. 1, it is the traditional coupling system of spatial light to fiber, in which the lens system could focus the spatial light on the fiber head to achieve the coupling [15]. Because the fiber is too small, the lens system needs to have high imaging precision. And what's more, the coupling efficiency is still low, sometimes, it is difficult to achieve effective coupling.

Shown as in Fig. 2, it is the new coupling system of spatial light to fiber, in which in the tapered fiber connector is adopted. Compared with the conmmon connector, the tapered fiber connector has larger light receiving area, it could improve the coupling efficiency.

In order to study the coupling characteristics of the tapered fiber connector, the following section will adopt Taylor series for analysis on propagation constant of the new connector.

3. The theoretical model of the power distribution characteristics of the new connector

The structure of the new fiber connector is shown in Fig. 3.

As shown in Fig. 3, the radius of cone bottom is r_i. Optical fiber radius is r_0, Cone length is L. Then, the relationship between the fiber radius and the cone length meet the following formula.

$$r(z) = r_i - \frac{z}{L}(r_i - r_0) \tag{1}$$

The refractive index of optical fiber core is n_1, the cladding refractive index is n_2. then, the time harmonic electromagnetic field can be expressed as the following [16].

$$E = E_0(r)e^{j\nu\varphi}e^{j(\omega t-\beta z)}$$
$$H = H_0(r)e^{j\nu\varphi}e^{j(\omega t-\beta z)} \tag{2}$$

In above formula, ω is angular frequency, β is the axial propagation constant, $E_0(r)$ is the radial electric field, $H_0(r)$ is the radial magnetic field. In the tapered connector, due to the change of the radius, β is changeable. We look the entrance point of the tapered connector as the origin and assume the radius changed slowly. Then, we can gain the following formula according to Taylor series.

$$\beta = \beta_0 + \left(\frac{\partial\beta}{\partial z}\right)z \tag{3}$$

In above formula, β_0 is the axial propagation constant at the point $z = 0$. According to Helmholtz equation, we can gain the electromagnetic field component as the following [17].

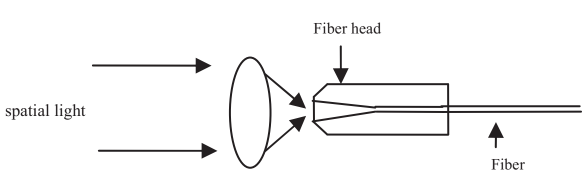

Fig. 2. The new coupling system of spatial light to optical fiber.

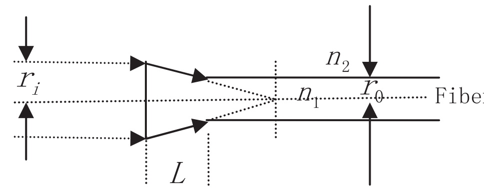

Fig. 3. The structure of the new fiber connector.

$$E_z^{(core)} = C_1 J_\nu(\gamma_1 r)e^{j\nu\varphi}e^{-j(\omega t-\beta z)}$$

$$H_z^{(core)} = C_2 J_\nu(\gamma_1 r)e^{j\nu\varphi}e^{-j(\omega t-\beta z)}$$

$$E_z^{(cladding)} = C_3 K_\nu(\gamma_2 r)e^{j\nu\varphi}e^{-j(\omega t-\beta z)}$$

$$H_z^{(cladding)} = C_4 K_\nu(\gamma_2 r)e^{j\nu\varphi}e^{-j(\omega t-\beta z)}$$

In above formula, , $\gamma_1 = \sqrt{k_0^2 n_1^2 - \beta^2}$, $\gamma_2 = \sqrt{\beta^2 - k_0^2 n_2^2}$. The parameters C_1 , C_2 , C_3 and C_4 are amplitude constants, J_ν and K_ν are Bessel functions with ν-order, the radial and angular component are as the following.

$$E_r = -\frac{j}{k_0^2 n^2 - \beta^2}\left(\beta\frac{\partial E_z}{\partial r} + \frac{\omega\mu_0}{r}\frac{\partial H_z}{\partial\varphi}\right)$$

$$E_\varphi = -\frac{j}{k_0^2 n^2 - \beta^2}\left(\frac{\beta}{r}\frac{\partial E_z}{\partial\varphi} - \omega\mu_0\frac{\partial H_z}{\partial r}\right)$$

$$H_r = -\frac{j}{k_0^2 n^2 - \beta^2}\left(\beta\frac{\partial E_z}{\partial r} - \frac{n^2\omega\varepsilon_0}{r}\frac{\partial H_z}{\partial\varphi}\right)$$

$$H_\varphi = -\frac{j}{k_0^2 n^2 - \beta^2}\left(\frac{\beta}{r}\frac{\partial H_z}{\partial\varphi} + \omega\varepsilon_0 n^2\frac{\partial E_z}{\partial r}\right)$$

Then, the power density in the tapered connector can be expressed as

$$S_z = \frac{1}{2}\mathrm{Re}[E_r H_\varphi^* - E_\varphi H_r^*] \tag{4}$$

The coupling efficiency can be expressed as

$$\eta = \frac{P_{core}}{P_{core} + P_{cladding}} = \frac{\int_0^{2\pi}\int_0^{r_a} S_{z1}\, rdrd\varphi}{\int_0^{2\pi}\int_0^{r_a} S_{z1}\, rdrd\varphi + \int_0^{2\pi}\int_0^{\infty} S_{z2}\, rdrd\varphi} \tag{5}$$

In above formula, P_{core} and $P_{cladding}$ are the power in the core and the cladding respectively.

4. The data analysis of the obtained formula

On the cut off conditions, $\gamma_2^2 \to 0$, for the fundamental mode [18],

$$J_0(\gamma_1 r_a) = 0 \tag{6}$$

Let $S_n = \gamma_1 r_a$, where n is a positive integer , corresponding to the solution of the equation , according to the formula (6) and (3), we can gain the following equation [19].

$$z^2\left(\frac{\partial\beta}{\partial z}\right)^2 + 2\beta_0 z\left(\frac{\partial\beta}{\partial z}\right) + \left[\beta_0^2 - k_1^2 + \left(\frac{S_n}{r_a}\right)^2\right] = 0 \tag{7}$$

Furtherly, we can get the solution of the formula $\partial\beta/\partial z$. Thus, Based on the above theoretical analysis, by establishing some parameters, we can calculate the relation between the coupling efficiency and the change of cone length. In the calculating process, let n_1 equal to 1.45, let the difference parameter between the core and cladding refractive index Δ be $\Delta = \frac{n_1^2 - n_2^2}{2n_1^2}$. Then, the numerical results of the simulation are