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Research on collimating characteristics of the emitted laser beam in free space optical communication system

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Abstract: A polymer straight tapered fiber collimation system with a fiber plano-convex lens coupled directly into the front-end was developed. We demonstrate that the cone angle and taper length of polymer straight tapered fiber have remarkable effects on the collimation performance based on the theory of rays propagation and geometrical optics. We show that the collimation accuracy improves obviously with small cone angle of long straight tapered fiber. In addition, the cone angle and taper length are further optimally designed so that both the coupling efficiency and collimation accuracy are well balanced and maximized in the collimating process. This study can benefit the collimation of the emitted laser beam in free space optical communication systems.

Key words: free space optical communication; collimation system; polymer straight tapered fiber; cone angle; taper length

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空间光通信系统发射光束的准直特性研究

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摘　要: 提出一种前端直接耦合光纤平凸透镜的聚合物直光锥光束准直系统。通过具体地对直光锥的端体结构参数进行优化设计以得到高耦合效率高准直精度的直接耦合式聚合物直光锥准直系统。并利用光线传输理论和仿真实验,论证了直光锥的锥角和锥长对准直效能的较大影响。结果表明,选择合适的锥角和锥长能达到十微弧度级的准直精度,能较好地满足空间光通信系统远距离发射和接收对于光束质量的要求。此外,理论数值和仿真实验同样验证了该直接耦合式直光锥准直系统对于较大发散角的发散光束具有较好的准直效果。

关键词: 空间光通信; 准直系统; 聚合物直光纤光锥; 中心角; 锥长

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0 Introduction

Semiconductor laser has been notably resurgent researched as a light source in free space optical communication (FSO)systems due to its advantages of small size, low power consumption, directed modulation and so on[1]. However, the divergence angle of the emitted laser beam from semiconductor laser is a large and asymmetric ellipse in space because of the waveguide structure [2]. In order to realize the non–relay transmission with high bit rate in long distance in the free space optical communication system, we should collimate and shape the emitted laser beam to make its divergence angle as small as possible, with the beam cross–section nearly circle to make full use of the energy. Nevertheless, the coupling loss from semiconductor laser into optical fiber as well as the divergence angle of emitted laser beam needs to be compressed approaching the diffraction limit to meet the requirements of practical free space optical communication system make the fiber collimation of semiconductor laser beam remain a challenging problem[3–4].

It is noted that single lens or lens group is mostly used to couple the emitted laser beam from semiconductor laser into optical fiber. Since the divergent characteristics of divergence angle, it can improve the coupling efficiency by both collimating the emitted laser beam through a single lens or a lens group and coupling with the circular cross section of the optical fiber[5–6]. Unfortunately, such a coupling mode has much higher requirements on the coaxial collimation of semiconductor laser, optical lens system and optical fiber, also with complicated structure, big size and inconvenient integrated package. Furthermore, although some works couple and collimate laser beam by optical fiber with tapered tip[7–8], coupling and collimating studies of polymer straight tapered fiber with micro lens melted into its front–end are not common in practical application, or even with straight tapered fiber to collimate the divergence angle of laser beam, actually, the cone angle and taper length of the straight tapered fiber are not further designed for the optimization[9–10]. Therefore, it is important to try to design the optimum straight tapered fiber collimation system to minimize the complexity of collimation system, increase the coupling efficiency, and thus further improve the collimation accuracy to fulfill the requirements of practical free space optical communication system.

1 Collimation system model

A polymer straight tapered fiber collimation system–based model is described in Fig. 1, where the fiber plano–convex lens is coupled directly into the front –end of straight tapered fiber, with which the Gaussian beam emitted by the semiconductor laser is focused and coupled into the straight tapered fiber. For the Gaussian beam of a half angle θ, it can be received by the optical fiber as long as the incident angle satisfies the total reflection conditions of optical fiber after its refraction through the fiber plano–convex lens, which in turn will expand the equivalent receiving angle of tapered fiber, and thus improve the coupling efficiency from laser source to tapered fiber[11]. On this basis, considering that it has reflective loss on the end face of optical fiber, the coupling efficiency can be further improved to increase the light use efficiency by both polishing treatment of optical surface of fiber plano–convex lens and plating a layer antireflection film on optical surface[12]. Besides, straight tapered fiber is used to collimate the divergence angles of laser beams both in meridional plane(i.e., fast axis direction)and sagittal plane (i.e., slow axis direction)to make the beam cross–section nearly circle.

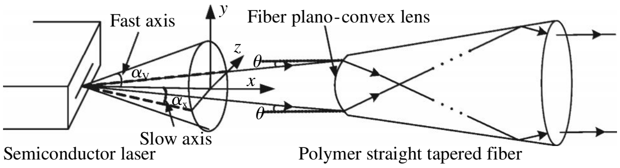

Fig.1 Collimating schematic diagram of polymer straight tapered fiber collimation system

Considering that the incident plane of fiber plano – convex lens is a spherical surface, which has equal convergent effect on rays of all directions, thus we demonstrate the following analysis by focusing on a selection of fast axis direction perpendicular to the junction plane. The collimating analysis figure of polymer straight tapered fiber with a cone angle δ in fast axis direction is shown as Fig. 2.

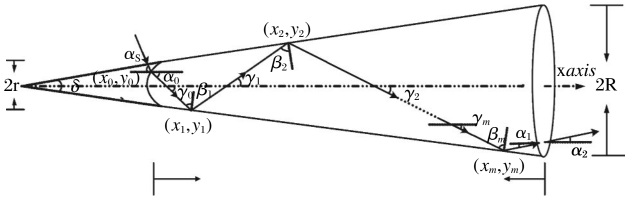

Fig.2 Analysis figure of straight tapered fiber collimating laser beam

Both the establishment of referenced coordinate system and the parameters involved in are given as follows. Taking the center point of straight tapered fiber's small end as the origin of coordinates, x axis is the central axis of straight tapered fiber, y axis is parallel to the fast axis direction of the laser beam. Rays with divergence angle α_s emitted by semiconductor laser have a intersection with the fiber plano-convex lens at point (x_0, y_0), total reflections thereafter occur on the inner surface of the fiber wall with a intersection order of (x_1, y_1), (x_2, y_2), $\cdots$, (x_m, y_m). β_1, β_2, $\cdots$, β_m are the incident angles of total reflection sequence, γ_0, γ_1, $\cdots$, γ_m are the included angles between the rays of $\overline{(x_{m-1}, y_{m-1})(x_m, y_m)}$ and axis. In particular, the values of total reflection times m here are taken as $1, 2, \cdots, m_{\max}$.

In order to seek for the relationship between the structural parameters of straight tapered fiber and collimating performance, an image model about collimation system is established using theory of rays propagation and geometrical optics. It is seen from Fig.2 that the coordinate of posterior point can be figured out by which of anterior point while the ray is propagating, that is, $y_1=y_0+(-1)^0(x_1-x_0)\tan\gamma_0$, $y_2=y_1+(-1)^1(x_2-x_1)\tan\gamma_1$, $\cdots$, thereupon, the general formula can be described as:

$$y_m=y_{m-1}+(-1)^{m-1}(x_m-x_{m-1})\tan\gamma_{m-1} \tag{1}$$

then, known by the geometrical theory of angles, here are:

$$\tan\frac{\delta}{2}=\frac{(-1)^{m-1}y_m-r_1}{2} \tag{2}$$

$$\gamma_m=\gamma_0-m\delta \tag{3}$$

thus, we can obtain the mathematical expression that the length L (i.e., x_m) of straight tapered fiber satisfies derived from Eq.(1), Eq.(2) and Eq.(3), it can be formulated as:

$$x_m=\frac{[(-1)^{2m-1}-1]r_1+[(-1)^{2m-1}\tan\frac{\delta}{2}-\tan\gamma_{m-1}]x_{m-1}}{\tan\frac{\delta}{2}-\tan\gamma_{m-1}},$$

namely,

$$x_{\mathrm{m}}=\frac{2r_1+[\tan\frac{\delta}{2}+\tan\gamma_{m-1}]x_{m-1}}{\tan\gamma_{m-1}-\tan\frac{\delta}{2}}=$$

$$\frac{2r_1+\{\tan\frac{\delta}{2}+\tan[\gamma_0-(\mathrm{m}-1)\delta]\}x_{m-1}}{\tan\gamma_{m-1}-\tan\frac{\delta}{2}}. \tag{4}$$

Here, r_1 is the radius of the small end of straight tapered fiber, γ_0 is the known parameter that can be computed from α_s with the refraction law of light, and is the total reflection times with value of $1, 2, \cdots, m_{\max}$. Obviously, cone angle δ and total reflection times m have a remarkable influence on the taper length x_m.

Due to the limit of the maximum total reflection times, we propose to find a set of limited conditions for details on the size of straight tapered fiber. As is known that all the rays coupled into straight tapered fiber can be refracted out from the outlet end through multiple internal total reflections, so limited conditions are specified by the incident angle that both all rays to reach the inner wall of straight tapered fiber each time must meet $\beta_m=\pi/2-\delta$ with $m=1, 2, \cdots, m_{\max}$ and all rays to reach the outlet end of straight tapered fiber must satisfy $\alpha_1\leqslant\delta/2$. According to geometrical optics theory, the angle relations from Fig. 2 can be formulated as: $\beta_1=\pi/2+\delta/2-\alpha_0$, $\beta_2=\pi/2+3\delta/2-\alpha_0$, $\beta_3=\pi/2+5\delta/2-\alpha_0$, $\cdots$, thus the incident angle of the m-th total reflection can be formulated as:

$$\beta_{\mathrm{m}}=\frac{\pi}{2}+\frac{(2m-1)\delta}{2}-\alpha_0, \tag{5}$$

up to this point, the limited condition for $m_{\max}$ can be calculated as follows:

$$m_{\max}\leqslant\frac{2\alpha_0-\delta}{2\delta}. \tag{6}$$

Only with total reflection times $m<m_{\max}$ can the laser

beam occur total reflections on the inner wall of straight tapered fiber and propagate with (γ_m=1, 2, ⋯, $m_{\max}$) decreasing to collimate the laser beam.

In addition, Fig. 2 also shows the further angle relations that $\beta_m+\alpha_1+\delta/2=\pi/2$ and $n_2\sin\alpha_1=n_1\sin\alpha_2$. On the premise of total reflection times $m<m_{\max}$, the divergence angle α_2 of the emitted laser beam collimated by the polymer straight tapered fiber collimation system can be expressed as:

$$\alpha_2=\arcsin\frac{n_2\sin\alpha_1}{n_1}=\arcsin\frac{n_2\sin(\frac{\pi}{2}-\frac{\delta}{2}-\beta_m)}{n_1}=\arcsin\frac{n_2\sin(\alpha_0-m\delta)}{n_1} \tag{7}$$

Where n_1 is the refractive index of the air medium, n_2 is the refractive index of polymer fiber, and α_0 is the refractive angle that can be obtained from $n_2\sin\alpha_0=n_1\sin\alpha_s$ with the refractive law.

It has been further seen from Eq.(5)and Eq.(7)that α_1 keeps decreasing while β_m is increasing, with total reflection times m increasing gradually as well as cone angle δ in a certain circumstance, namely, the divergence angle α_2 keeps decreasing with the beam collimating performance being better and better. Meanwhile, Eq.(5) and Eq.(7)also show that cone angle δ and total reflection times m have a remarkable influence on collimating performance of laser beam through the polymer straight tapered fiber collimation system, as for a fixed cone angle δ, the limited condition for total reflection times m determines the taper length, thus the collimating performance strongly depends on the change of cone angle and taper length. As a matter of fact, the rationality and validity of the conclusion above will be further performed in Sec.2.

2 Numerical results and analysis

In this section, we use the relationship between structural parameters(i.e., radius of the small end r_1, cone angle δ and taper length x_m)of straight tapered fiber in Eq.(4) and divergence angle α_2 after collimation in Eq.(7) to analyze the performance of direct-coupling polymer straight tapered fiber collimation system with the Gaussian laser beam emitted by semiconductor laser.

For polymer straight tapered fiber collimation system, the emphases are placed on proper setting of some parameters based on free space optical communication system in practical application to improve both the coupling efficiency and collimation accuracy. Taking the propagation law of Gaussian beam into consideration (in view of Ref.[13] and [14]), we should better choose a fiber plano-convex lens with short focal length F and high refractive index n_2 under machining process, place the fiber plano-convex lens at the location of beam waist before collimation when the collimation system is assembled, and try to make the curvature radius of fiber plano-convex lens two times of the radius of incident beam spot. We select the GaAs-AlGaAs semiconductor laser of 810 nm wavelength used in simulation experiment of free space optical communication of America NASA[15]. Hereby, parameters involved in simulation procedure are selected as follows: the optical wavelength λ=810 nm, the beam waist of emitted laser beam from semiconductor laser is taken to be =0.25 mm for reasonable parameters with F= 0.55 mm, r_1=0.3 mm, n_1=1 and n_2=1.491, the maximum divergence angle in fast axis direction is $\alpha_s=\pi/6$. Some simulation results are compiled in Fig. 3-7.

Fig. 3 and Fig. 4 show the divergence angle α_2 of the emitted laser beam after collimation and taper length x_m with different cone angles via the times of total reflection m, where the divergence angle α_2 keeps decreasing and taper length keeps increasing with the increase of total reflection times m as well as cone angle δ in a certain circumstance, respectively. However, the divergence angle α_2 decreases rapidly while the taper length increases dramatically with the cone angle increasing gradually. It is noted that the optimum collimating performance we are seeking for is no doubt at the cost of the enlargement of collimation system under this situation. Therefore, it is necessary to properly design the cone angle and taper length such that the polymer straight tapered fiber collimation system can achieve higher accuracy.

For the further analysis, the performance comparisons of small cone angles and big cone angles are carried out, 0.2°, 0.5° and 1° for small cone angles with 2° and 5° for big cone angles are chosen, respectively, as shown in Fig. 5 and Fig. 6. It can be seen that both small cone angle of long tapered fiber and big cone angle of short tapered fiber can achieve the same collimating performance. For instance, using the straight tapered fiber collimation system which has a cone angle of 0.2° to compress the laser beam with a divergence angle of 30° in fast axis direction to 0.958 3°, the taper length needed is 48.5 mm, correspondingly, if the cone angle is 2°, to reach the same compressed angle, it needs 32.9 mm in terms of the taper length. Although bigger cone angle is much more beneficial to reduce the beam divergence angle, the accuracy of final compressed angle will decrease with the increase of cone angle, obviously, the straight tapered fiber with a cone angle of 5° can quickly reduce the divergence angle from 30° to 3.983 1°, but the final collimating accuracy is only 3.983 1°, for the cone angle of , despite of slow decrease for divergence angle, the collimating accuracy can eventually reach 0.205 1°. By comprehensive consideration, small cone angles of long tapered fiber are selected to seek for the best collimating performance.

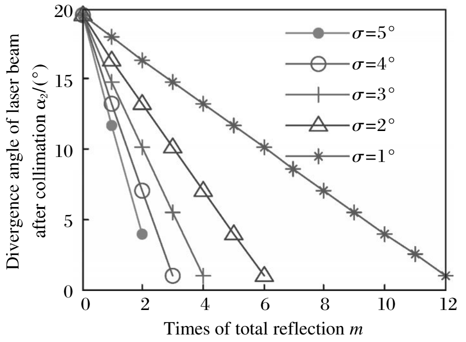

Fig.3 Divergence angle α_2 of emitted laser beam after collimation vs times of total reflection m for different cone angle δ

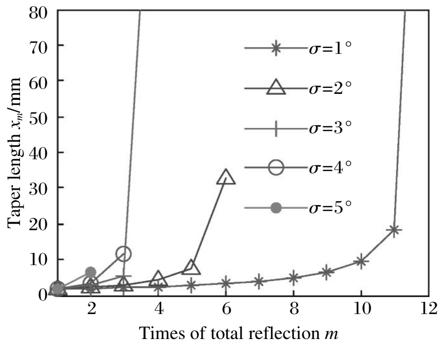

Fig.4 Taper length as a function of times of total reflection m for different cone angle δ

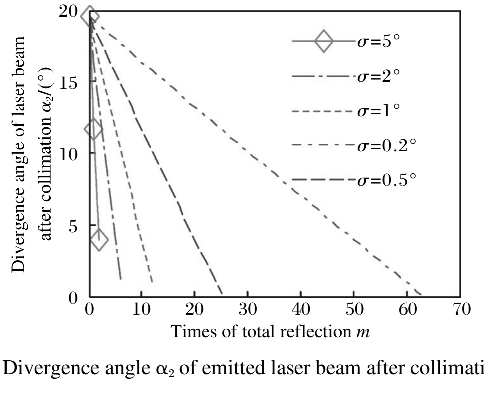

Fig.5 Divergence angle α_2 of emitted laser beam after collimation vs total reflection times m for different cone angle δ

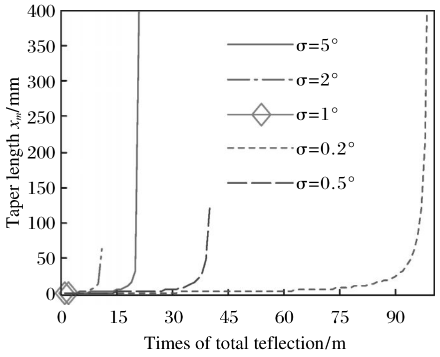

Fig.6 Taper length as a function of total reflection times for different cone angle δ

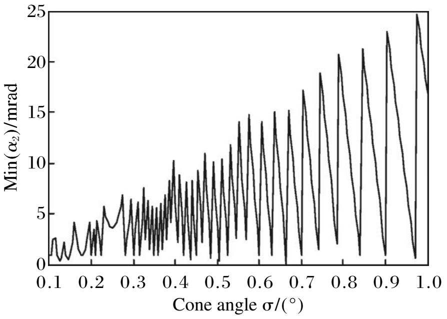

Fig.7 Minimum divergence angle min(α_2)of emitted laser beam as a function of different cone angles δ of straight tapered fiber

With regard to small cone angles, the taper length calculated based on Eq.(4)are greater than 2 m when the cone angles are less than 0.1°, which increase the volume and complexity of collimation system, and the collimation accuracy can only reach 0.958 3° through collimation system with the cone angles more than 1°, which does not meet the practical requirements (i.e., dozens of microradian)of divergence angle of emitted laser beam in free space optical communication system. Thus, Fig. 7 is given to seek for the best collimation accuracy by appropriate cone angles, which are greater than 0.1° and less than 1°.

As is shown in Fig.7, with increase in cone angles, the minimum divergence angle of the emitted laser beam increases in a similar way of sinusoidal fluctuations, following with a trend of increasing as a whole. However, taking the effects of cone angle and taper length on collimation performance into account, it is noted that the collimated laser beam can obtain the minimum divergence angle of 13.42 μrad when the cone angle is 0.665°, with taper length corresponding to 60.3 mm. Such a high degree of collimation accuracy as well as very appropriate system volume could meet consistently over the beam quality requirements for remote transmission and reception in free space optical communication system.

Furthermore, the semiconductor laser selected in this paper possesses an emitting characteristic that the maximum divergence angle in meridional plane is the range of 23°–39°[14]. On the premise of their respective optimum cone angles, Fig.8 is given to show the minimum divergence angle of the emitted laser beam as a function of different cone angles of the straight tapered fiber via the polymer straight tapered fiber collimation system.

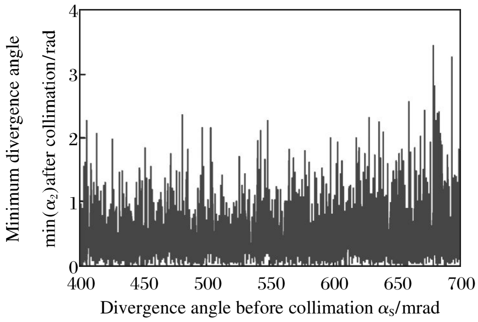

Fig.8 Minimum divergence angle min(α_2) of emitted beam after collimation as a function of divergence angle α_s of emitted beam before collimation

It can be seen from Fig. 8 that the polymer straight tapered fiber collimation system put forward in this paper has preferable performance in collimating laser beams, it also reveals that divergence angles can be kept within 25 μrad through the collimation system. Even the largest divergence angle of laser beam emitted from the semiconductor laser is 39°, the collimated angle can be 6.51 μrad after collimation, which can fully meet the beam quality requirements in free space optical communication system. Such a high degree of collimation accuracy could meet consistently over the beam quality requirements for remote transmission and reception in free space optical communication system. Therefore, this collimation system with high accuracy has wide application prospects.

3 Conclusion

In this paper, we have developed a polymer straight tapered fiber collimation system with fiber plano–convex lens coupled directly into the front–end. Because of the optimum designs of structural parameters both for fiber plano–convex lens and especially for straight tapered fiber, the polymer straight tapered fiber collimation system has demonstrated an excellent performance of collimating the emitted laser beam in free space optical communication system. The excellent collimation performance of the collimation system with appropriate cone angle and taper length has been evaluated and compared with those with big cone angles of short straight tapered fiber and small cone angles of long straight tapered fiber in the simulation examples.

In addition, the collimation accuracy improves obviously with small cone angles of long straight tapered fiber, where the preferable cone angle δ of 0.665° and taper length of 321.2 mm have been found with respect to the highest collimation accuracy of 13.417 9 μrad within the scope of our study, respectively. Furthermore, the simulation results have also proved that the polymer straight tapered fiber collimation system had good performance for the divergent laser beam with large divergence angle. This research can be used in the collimation of the emitted laser beam in free space optical communication systems.

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