Analysis of the enhanced coupling efficiency for different profile curves of special optical taper*

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For enhancing the coupling efficiency between the beam and the photodiode, a special optical taper is proposed for receiving optical signal. Based on the circular symmetric structure of special optical taper, the profile curve equations of it are deduced, including the trigonometric function type, parabolic type and exponential type. Moreover, the coupling efficiencies for special optical tapers with different profile curves are studied. The relationships of incident position, incident angle and coupling efficiency are analyzed. Finally, the comparison of coupling efficiency analytical results is also given.

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With the development of new communication technology, such as free-space communication[1], laser radar[2] and scattering optical communication[3], the higher optical signal receiving quality is required, including high sensitivity, high coupling efficiency and wide angle receiving. However, some complex environmental factors, such as weather conditions[4], atmospheric turbulence[5] and pedestal vibration[6], are easy to affect the coupling efficiency of optical signal receiving system. So how to reduce the influence of beam jitter caused by environment or pedestal vibration is a crucial problem. Many researchers have studied it. For example, Hranilovic et al[7] researched the photodiode with large receiving area, it could capture the entire jittering beam, but it reduced the transmission rate and limited the operation speed. Lee C. Chen et al[8] proposed a novel fiber tapering shape to increase the acceptance angle of a compound parabolic concentrator, but the input aperture was so small that the concentrator was sensitive to the beam jitter. Ali Javed Hashmi et al[9] investigated the telescope array receivers for deep-space inter-planetary optical communication, but the receiving system was rather complex. Thereby, it is necessary to study a new optical component to get high coupling efficiency between the beam and the photodiode.

In this paper, a special optical taper is proposed to receive the optical signal. And the profile curve equations of the special optical taper are deduced. The enhanced coupling efficiency for different profile curves of the special optical taper is discussed. Finally, the comparison of coupling efficiency analytical results is also given.

The special optical taper is solid and made by pure silica rod in graphite furnace[10,11]. The large input aperture can collect more optical signals, and a much smaller output aperture can connect the photodiode conveniently. The schematic diagram of the special optical taper is shown in Fig.1.

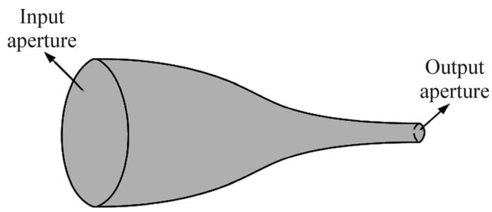

Fig.1 Schematic diagram of the special optical taper

In Fig.1, the profile curve of optical taper has many types, such as trigonometric function, exponential function and parabolic function. With this special structure, it can connect with photodiode easily and offer high beam jitter tolerance. The longitudinal cross-section curve of the special optical taper is shown in Fig.2.

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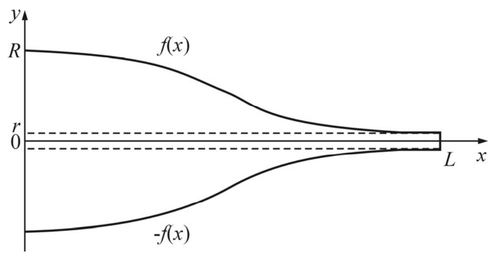


Fig.2 The longitudinal cross-section curve of the special optical taper

In Fig.2, x axis represents the longitudinal coordinate of taper length, y axis represents the radius of cross-section at the corresponding x-coordinate, R is the radius of large input aperture, r is the radius of small output aperture, L is the length of optical taper, and $f(x)$ represents the upper profile curve equation. Because of the circular symmetric structure of special optical taper, the longitudinal cross-section curve is analyzed without affecting the final theoretical analysis and calculation results.

Firstly, the profile curve equation of optical taper is deduced. Assume that the generatrix of special optical taper is the trigonometric function type as

$$f(x)=a\cos(\omega x)+b . \quad (1)$$

And half period of this equation is supposed as L, so it can be obtained that

$$\omega=\frac{\pi}{L} . \quad (2)$$

In addition, Eq.(1) should satisfy the boundary conditions of

$$\begin{cases} f(x)|_{x=0}=R \\ f(x)|_{x=L}=r \end{cases} . \quad (3)$$

Substituting Eqs.(2) and (3) into Eq.(1), we can get that

$$a=\frac{R-r}{2},\ b=\frac{R+r}{2} . \quad (4)$$

So the analytic expression of Eq.(1) is rewritten as

$$f(x)=\frac{R-r}{2}\cos(\frac{\pi}{L}x)+\frac{R+r}{2} . \quad (5)$$

The size of special optical taper is much larger than the wavelength of incident light, so geometrical optics is used for analyzing the optical taper. When the light passes through the interface of two different media, it follows the laws of reflection and refraction as shown in Fig.3.

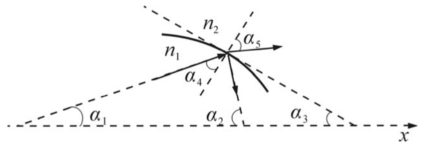


Fig.3 Principle diagram of geometrical optics in the interface of two different media

In Fig.3, the arc is a portion of the special optical taper's profile curve, x axis represents the optical axis, n_1=1.458 is the refractive index of taper, n_2=1 is the refractive index of air, α_1 is the angle between incident light and x axis, α_2 is the angle between reflected light and x axis, $\alpha_3=\tan^{-1}f'(x)$ is the angle between tangent line at the reflection point and x axis, α_4 is the angle between incident light and normal line, and α_5 is the angle between refracted light and normal line. By the geometrical optics principle, we can obtain

$$\alpha_2=\alpha_1+2\alpha_3 . \quad (6)$$

Eq.(6) represents the relationship between the ray traces before and after the reflection at the reflection point. According to the total reflection principle, the critical angle C is $\sin^{-1}(n_2/n_1)$. If $\alpha_4>C$, the energy values of reflected and incident light are the same. If not, some portion will be lost because of the refraction. The reflection index R is determined by the Fresnel equation as

$$R=\frac{1}{2}\left\{\left[\frac{\sin(\alpha_5-\alpha_4)}{\sin(\alpha_5+\alpha_4)}\right]^2+\left[\frac{\tan(\alpha_4-\alpha_5)}{\tan(\alpha_4+\alpha_5)}\right]^2\right\} , \quad (7)$$

where $\alpha_4=\frac{\pi}{2}-\alpha_1-\alpha_3$ and $\alpha_5=\sin^{-1}\left[n_1\frac{\sin(\alpha_4)}{n_2}\right]$. Then the relationship between the light energy before and after the reflection at the reflection point is obtained further. Based on the geometrical optics principle, the response of taper to the ray can be then analyzed, including the ray trace and the energy of light exiting at the small aperture. Fig.4 shows the different situations of light transmitting in the optical taper.

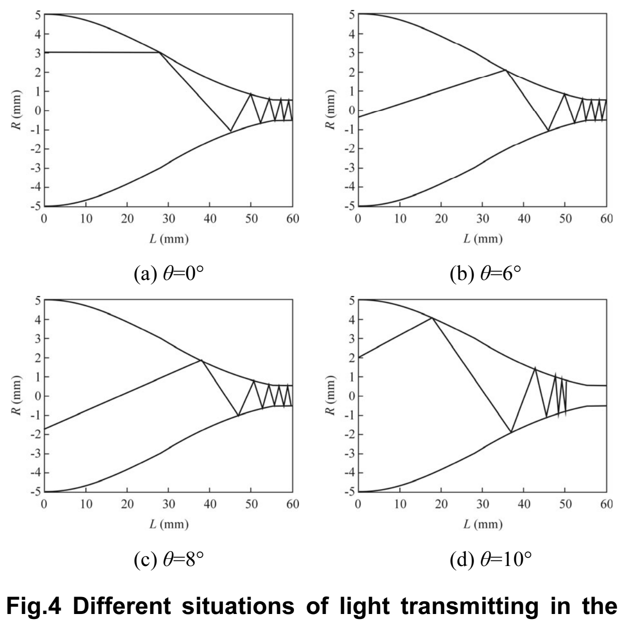


Fig.4 Different situations of light transmitting in the optical taper with different incident angles and energy losses

In Fig.4, the initial energy is assumed as 1. When θ=0°, the light satisfies the total internal reflection, and the energy of the emergent light is 0.959 872. When θ=6°

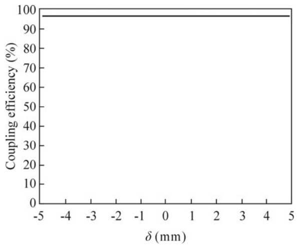
and 8°, the light does not satisfy the total internal reflection, and the energy of the emergent light is 0.002 256 49 and 0.185 788, respectively. When θ=10°, the light can't transmit because of the fold-back situation, so the energy of the emergent light is 0. The incident light can be characterized by the incident position δ and the incident angle θ, so different parameters can lead to different light transmitting results.

Moreover, when the profile curve is the exponential function type or the parabolic function type, we can also get the similar conclusion. Based on the above theoretical analysis results, the coupling efficiencies of three kinds of optical tapers are analyzed below, respectively.

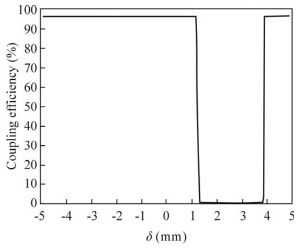
The coupling efficiency of optical taper is affected by the profile curve type. Through the above analysis, it can be concluded obviously that the larger the radius of output aperture, the higher the spatial tolerance. But limited by the size of photodiode, the output aperture can't be too large, so the output aperture is chosen as 1 mm. And the input aperture should not be too small, otherwise increasing the effective aperture of the photodiode will be meaningless. Finally, the input aperture is chosen as 10 mm, and the length of optical taper is 60 mm.

Then, with large input aperture R=5 mm, small output aperture r=0.5 mm and taper length L=60 mm, coupling efficiencies for optical tapers with different profile curves, including trigonometric function type, parabolic type and exponential type, are obtained.

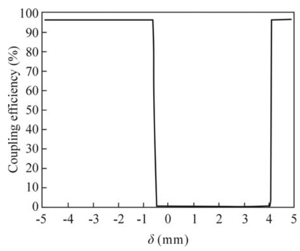
When the profile curve is the trigonometric function type, we simulate the light incident on any position of the optical taper input aperture at a given angle, and then calculate the coupling efficiency by changing the incident position. The coupling efficiency as a function of incident position δ for different incident angle θ is shown in Fig.5.



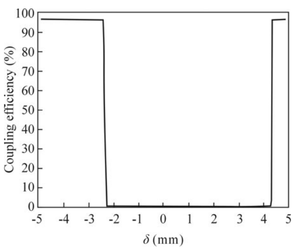
(a) θ=0°



(b) θ=3°



(c) θ=6°



(d) θ=9°

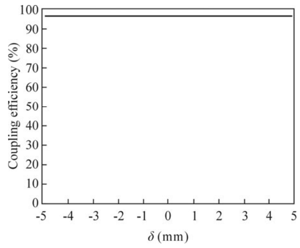
Fig.5 The coupling efficiency as a function of incident position δ with different incident angles in trigonometric type taper

In Fig.5, it is assumed that the incident position δ at large input aperture is from –4.9 mm to 4.9 mm. We can see that when the incident angle θ is 0°, light can transmit through the optical taper with high coupling efficiency whatever δ is. When θ is 3°, it presents different energy losses while δ is from 1.2 mm to 3.9 mm, which is due to not satisfying the total internal reflection. When θ is 6°, the coupling efficiency becomes zero while δ is from 0.5 mm to 3.6 mm because of the fold-back situation. When θ is 9°, the range, in which coupling efficiency is zero, becomes wider.

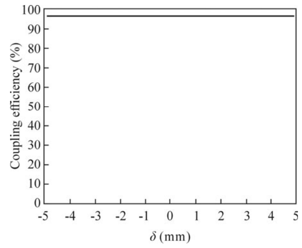
The profile curve equation of parabolic type taper is deduced as

$$f(x)=\frac{r-R}{L^2}x^2+R\,, \tag{8}$$

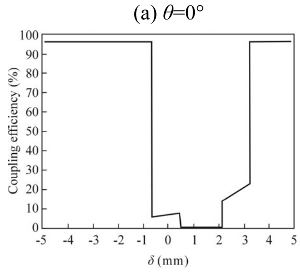
of which the derivation process is the same as that of the trigonometric function type. And the coupling efficiency as a function of incident position δ for different incident angle θ is shown in Fig.6.



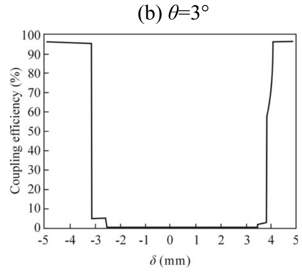
(a) θ=0°



(b) θ=3°



(c) θ=6°



(d) θ=9°

Fig.6 The coupling efficiency as a function of incident position δ with different incident angles in parabolic type taper

It is also assumed that the incident position δ is from –4.9 mm to 4.9 mm. It can be obtained that when the incident angle θ is 0°, light can transmit through the optical taper with high coupling efficiency whatever δ is. When θ is 3°, we can also get high coupling efficiency no matter where the light is incident on the input aperture. When θ is 6°, it presents different energy losses while δ is from –0.6 mm to 3.2 mm due to not satisfying the total internal reflection. When θ is 9°, the coupling efficiency becomes zero while δ is from –2.4 mm to 3.4 mm because of the fold-back situation.

The profile curve equation of exponential type taper is deduced as

$$f(x)=R\mathrm{e}^{\frac{\ln(\frac{r}{R})}{L}x}\,, \tag{9}$$

of which the derivation process is also the same as that of the trigonometric function type. And the coupling efficiency as a function of incident position δ for different incident angle θ is shown in Fig.7.

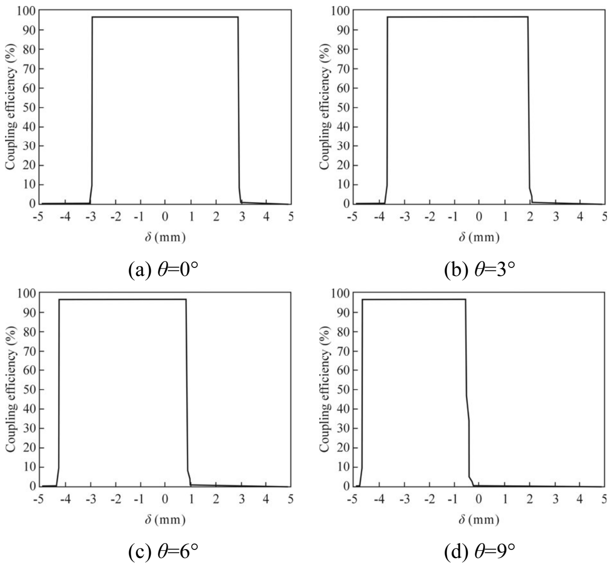


Fig.7 The coupling efficiency as a function of incident position *δ* with different incident angles in exponential type taper

It is also assumed that the incident position δ is from –4.9 mm to 4.9 mm. It can be obtained that when the incident angle θ is 0°, light can transmit through the optical taper with high coupling efficiency only while δ is from –2.9 mm to 2.9 mm. And the range of high coupling efficiency becomes small with the increase of incident angle.

Through the above analyses, it can be seen that different type tapers have the different performance on optical receiving. When θ is 0°, light can transmit through the optical taper with high coupling efficiency whatever δ is, only while the optical taper is trigonometric function type or parabolic type. When θ is 3° and 6°, light can transmit through the optical taper with high coupling efficiency no matter where the light is incident on the input aperture, only while the optical taper is parabolic type. Thereby, the parabolic type optical taper has the best tolerance to beam jitter.

In this paper, a special optical taper is proposed to receive the optical signal in complex environment. Different profile curve equations of optical taper are deduced, including trigonometric function type, parabola type and exponential type. For different kinds of optical tapers, the relationships of incident position, incident angle and coupling efficiency are analyzed. By comparing the analytical results, it can be concluded that the parabolic type optical taper has the best tolerance to beam jitter and can enhance the coupling efficiency between the beam and the photodiode. Thereby, the special optical taper can be applied to the optical signal receiving in free-space communication, laser radar, scattering optical communication, etc.

References

[1] Xiang Jin-song, Ma Sheng-ming, Liu Fei and Yang Song, Journal of Optoelectronics·Laser **24**, 687 (2013). (in Chinese)

[2] Min Seok Oh, Hong Jin Kong, Tae Hoon Kim, Keun Ho Hong and Byung Wook Kim, Optics Communications **283**, 304 (2010).

[3] Jingyue Fang, Hailiang Zhang, Honghui Jia, Hongwei Yin, Shengli Chang and Shinqiao Qin, Chinese Optics Letters **8**, 478 (2010).

[4] Kemal Davaslıoğlu, Erman Çağıral and Mutlu Koca, Optics Express **18**, 16618 (2010).

[5] Li Ming, Li Shu-ming and Yang Shao-wen, Journal of Optoelectronics·Laser **24**, 710 (2013). (in Chinese)

[6] Antonio Garc´ıa-Zambrana, Beatriz Castillo-V´azquez and Carmen Castillo-V´azquez, Optics Express **20**, 2096 (2012).

[7] S. Hranilovic, IEEE Journal of Selected Topics in Quantum Electronics **12**, 859 (2006).

[8] Lee C. Chen, Andy L. Y. Low and Su F. Chien, Applied Optics **43**, 5923 (2004).

[9] Ali Javed Hashmi, Ali Asghar Eftekhara, Ali Adibi and Farid Amoozegar, Optics Communications **283**, 2032 (2010).

[10] Xinghu Fu, Zhenyi Chen, Qiang Guo, Fufei Pang and Tingyun Wang, Optical Engineering **49**, 065002 (2010).

[11] Fu Xing-hu, Chen Zhen-yi, Guo Qiang, Pang Fu-fei and Wang Ting-yun, Optoelectronics Letters **7**, 92 (2011).