

Hollow-core tapered coupler for large inner diameter hollow-core optical fibers

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A novel hollow-core tapered coupler has been theoretically designed and fabricated by fiber drawing machine. The coupler's inner wall is coated with a polycrystalline GeO₂ film. The coupling loss of hollow-core tapered coupler is about 0.2 dB. Hollow-core tapered coupler reduces the transmission loss of hollow-core optical fiber (HCOF) by 0.5 dB/m, therefore the coupler is suitable for coupling high power CO₂ laser in industrial application.

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A ZnSe lens with a focal length of 100 mm has been used to couple a large diameter laser beam, which has beam diameter of 7 mm, into a hollow-core optical fiber (HCOF). The focused spot size is about 0.5 mm and the coupling angle is 4 degree. The laser beam is reflected nearly 70 times in the HCOF, the inner diameter and the length of the HCOF are 1.2 mm and 1.0 m, respectively. If the reflection attenuation of the HCOF inner surface is considered, the transmission loss will be more significant than the coupling loss. Matsuura and others designed a tapered coupler for small diameter HCOFs with a transmission loss of only 0.5 dB^[1,2]. However, that type of coupler is not ideal for the fibers with inner diameter more than 1.2 mm which are being used to transmit high power CO₂ laser. Now, we developed a hollow-core tapered coupler to meet the need.

Considering the parameters such as laser beam diameter, the focused spot size on the lens and the HCOF inner diameter etc., we couple the laser energy into the HCOF. If the HCOF inner diameter is larger than the focused spot size, in order to reduce the transmission loss, we can change the coupling method. According to the ray optics, if the wavelength is far less than the HCOF inner diameter, we can obtain an expression of $|AB|$ which is the beam transmission distance between two reflection points in the HCOF as shown in Fig. 1.

$$|AB| = \frac{d}{\tan \theta}, \quad (1)$$

where d is the HCOF inner diameter, θ is the half angle of the beam cone formed by the focusing lens. Similarly, we can obtain the number n which is the reflection times of the incident beam inside the HCOF per meter. The relation between n and θ is

$$n = \frac{1}{|AB|} = \frac{\tan \theta}{d}. \quad (2)$$

Suppose the reflectivity of the inner wall is ρ , the output power w is

$$w = \rho^n w_0, \quad (3)$$

where w_0 is the input power, n is given by the Eq. (2), and the total HCOF transmission loss will be

$$a = -10 \lg \frac{w}{w_0} = -10n \lg \rho = -\frac{10 \lg \rho}{d} \tan \theta. \quad (4)$$

It can be illustrated in Fig. 2.

Figure 2 shows that the larger the incident angle θ is, the higher the transmission loss the HCOF is. The reflectivity of the inner surface depends on the incident angle θ , too. Providing θ meets the total reflection requirements, we can omit the effects of θ . From Eq. (4), we know that the HCOF transmission loss depends on the film material reflectivity ρ on the inner wall and the incident angle θ . However, the reflectivity ρ is an intrinsic properties of the reflecting film, we will not discuss in this paper. From the Eq. (2) and Fig. 2, we know that the incident angle θ should be as small as possible in order to decrease the number of reflections. Therefore, we should design a hollow-core tapered coupler to make the incident laser beam paralleled with the axis of the HCOF to a great extent, as shown in Fig. 3.

In Fig. 3, for making the output laser beam 1 paralleled to the axis of the fiber, a reflector is placed at point A to make the angle equalized to $\theta/2$ with the axis. This obeys the geometrical optics principles. The coordinate of the point A is $x = l \cos \theta$ and $y = l \sin \theta$. Therefore, the function $y = f(x)$ can be obtained. We rotate the curve $y = f(x)$ around the axis and get a circular cone, as shown in Fig. 4, which is the hollow-core tapered coupler.

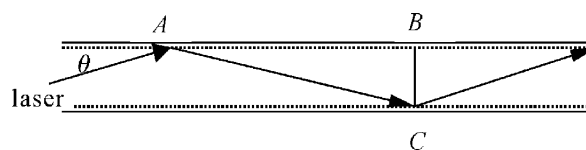


Fig. 1. Schematic graph of the laser beam reflection in the HCOF.

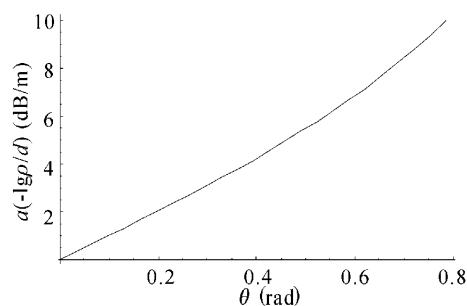


Fig. 2. Relationship between transmission loss (a) and incident angle (θ).

Table 1. HCOF Transmission Loss Comparison, Coupling Energy Using Tapered Coupler and Lens

	Length of HCOF (m)	Input Power of Optical Fiber (W)	Output Power of Optical Fiber (W)	Transmission Loss (dB)
Coupling with the Lens	0.5	33	30.0	0.41
	1.0	33	26.4	0.97
	1.5	33	23.7	1.40
Coupling with the Lens and Tapered Coupler	0.5	33	31.3	0.23
	1.0	33	29.5	0.49
	1.5	33	27.8	0.74

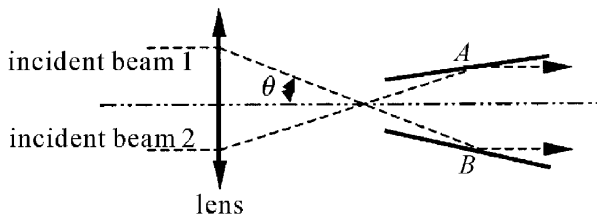


Fig. 3. Reflection of laser beam in hollow-core tapered coupler.

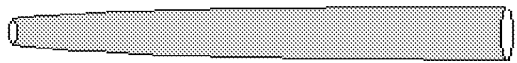


Fig. 4. Schematic view of the hollow-core tapered coupler.

The hollow-core tapered coupler is made of a big silica tube by a Fiber Drawing Machine. The mass of the silica is constant during the drawing process, so the relationship between the inner diameter of the coupler and the drawing speed v can be expressed as

$$v \propto \frac{1}{d^2}. \tag{5}$$

Because d equals to $f(x)$, v can be expressed as

$$v \propto \frac{1}{[f(x)]^2}. \tag{6}$$

The Fiber Drawing Machine is controlled by computer and the v function is applied to the computer. Many hollow-core tapered couplers have been made successfully, and the inner walls of the couplers are deposited with the polycrystalline $\text{GeO}_2^{[3]}$.

We measure the HCOF transmission loss with the coupler as Fig. 5.

The hollow-core tapered coupler is 42.3 mm in length, the inner diameter of the input end is 0.6 mm and the output is 1.3 mm. The length of the straight HCOF is 1 m and its inner diameter is 1.5 mm. We found that this kind of HCOF decreases the transmission loss by about 0.5 dB/m compared with that when laser energy is coupled into the HCOF directly by a lens, see Fig. 6. In order to get rid of the influence of the different characteristics of the HCOF, we use the same HCOF and the same input power. The results are shown as Table 1.

We can conclude that if the hollow-core tapered coupler is a conical optical taper, the transmission loss will be reduced from 0.97 to 0.49 dB/m, that is decreased by

about 0.5 dB/m.

The diffraction on the coupler has little effect on the HCOF loss. The wavelength of the CO_2 laser is $10.6 \mu\text{m}$, and the inner diameter of the coupler's output end is 1.3 mm, so the laser beam will diffract at the output end. According to Fraunhofer diffraction principles, we can obtain the following equation in one order Bessel function.

$$I = A_0^2 \frac{J_1^2(\pi d \sin \theta / \lambda)}{(\pi d \sin \theta / 2\lambda)^2} = I_0^2 \frac{J_1^2(122.6\pi \sin \theta)}{(61.3\pi \sin \theta)^2}, \tag{7}$$

where I is the intensity of the laser, θ is the angle of the diffraction, and d is the inner diameter of the coupler.

Figure 7 shows that most laser energy concentrates in Airy disk, which is the center of the coupler, and only a little bit of laser energy diverges with a small diffraction angle from the original direction. The larger diffraction angle is, the less laser energy loses. We can conclude that there is about 1% of the laser energy within the diffraction angle region larger than 0.02rad. Therefore, the diffraction effects are minor for larger diameter hollow-core tapered couplers. Especially, when the conical coupler is attached to the HCOF tightly,

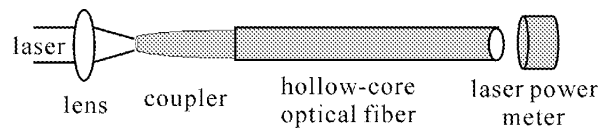


Fig. 5. Experimental setup for measuring HCOF transmission loss.

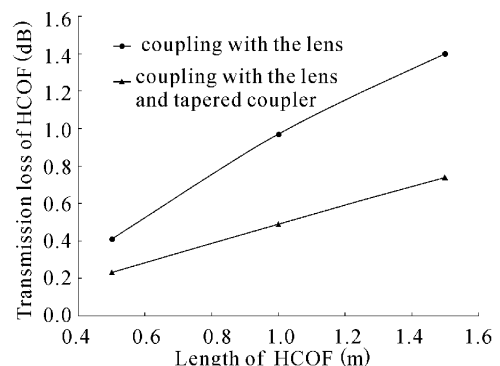


Fig. 6. Measured HCOF transmission loss with and without hollow-core tapered coupler.

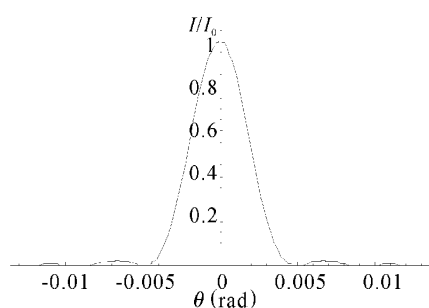


Fig. 7. Relationship between intensity of the laser and diffraction angle.

the diffraction will only affect the incident angle in the HCOF.

The laser beam is turned into a cone after being focused by lens. However, this kind of laser beam will cause additional loss, which will affect the transmission performance. But if a the hollow-core tapered coupler is used to couple the laser beam after focused by lens, we can make most of the laser beam meet the total reflection requirements. All these properties reduce the transmission loss greatly. The transmission loss caused by the taper coupler itself accounts for the material's absorption char-

acteristics. However, although the inner diameter at the output end is 1.3 mm which is much bigger than $10.6 \mu\text{m}$, the output beam diffraction at the output end of the taper coupler is to be expected, and along with the scattering effect of the incident beam caused by the rough inner surface, there will be a little bit power diverging from the output beam at the output end. The diverged power will either not be able to enter the HCOF or its reflection angle will be enlarged in the HCOF, eventually the coupling loss is increased. In order to decrease the effect of the diffraction, we should lessen the absorption of the material, reduce the roughness and unevenness of the surface as possible as we can, and make the taper coupler's big end attached to the HCOF tightly.

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