Low-Loss Coupling from Coated Plano Convex Lens to Single Mode Solid Core Fibers Laser by Lensing Scheme

Noor Zamin Khan (✉ noorzamin@mail.ustc.edu.cn)

University of Science and Technology of China

Muhammad Sohail

Shenzhen University

Noor Zamin Khan

University of Science and Technology of China

Ikhtisham Mehmood

Shenzhen University

Tenghui Chen

Shenzhen University

Sayed Ali Khan

University of Science and Technology of China

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Abstract

For the first time, to the best of our knowledge, we experimentally demonstrated the new scheme for a coated Plano-convex lens (CPCL) fiber with a maximum coupling efficiency ($\eta_{\max}$). In the single-mode solid core fiber (SMSCF), the fiber coupling efficiency is $\sim 68\%$ injected pump power 632.8 nm (1.5-dB loss was measure with a laser diode) which is difficult to achieve by using conventional technology, and also we reported, without fiber tapering technology has been used to realize low loss coupling from CPCL to SMSCF at low power level, and compare with published data. This is very useful for implementing all optical fiber systems. In addition, it also investigates the effect of bending the output power and beam profile of SMSCF. The Gaussian-like output beam profile is maintained up to $\cong 7\text{ cm}$ bending radius. The output mode field with good beam quality shows the mode filtering characteristics of SMSCF. Finally, the result of the fiber coupling efficiency (FCE) illustrates that the scheme of the lens coupling system is the most sensitive scheme to the misalignment and the lensing scheme is the least sensitive to misalignment.

1. Introduction

Due to its enormous band-width and appropriateness for long-distance data transmission, light propagation into single-mode solid core fiber with excellent efficiency has recently gained a tremendous application or claim in optical communication.¹⁻² Although shooting laser light into SMFs is a difficult process, theoretically predicted FCE can be obtained with proper alignment. Hollow-core fiber (HCF) offers low non-linearity and low group velocity dispersion, making it ideal for high-power beam delivery, ultra-short pulses, and gas-based non-linear optics applications.³⁻⁸ In order to obtain low confinement loss in the anti-resonance hollow-core fiber, the core diameter is typically between 50 and 100 μm . (HCF).⁹⁻¹⁰ By adjusting the structure and coupling parameters, a high fiber coupling efficiency and good process parameters can be achieved. Various optical fiber coupling strategies have been employed in previous studies to get a greater FCE. Typically, a unique cavity structure adjusts the spot from the laser light source, increasing the energy, or output power, of the laser that enters the optical fiber.

K.Z. Aghaie and colleagues employed SMFs with adjusted parameters to reduce splicing loss to $\sim 0.79\text{ dB}$ in 2010.¹¹ An analytical approach based on the theory of Gaussian beam propagation is used to determine the CE of a hemispherical lensed fiber with high CE and low operating distance between SMFs and laser diodes.¹² The background of nonlinear fiber optics field (NFOF) has been mainly subjected by SMF's because of their high bandwidth and structure simplicity over the last few years.¹³ Nonlinear multimode and multicore optical fibers (MMFs) have recently emerged as a viable solution to address many crucial long-standing problems, such as the capability promotion regime of telecommunications systems using the spatial division multiplexing technique. Adaptive optics (AO) technology in SMF's free-space optical communications system (SOCS) has been shown to effectively enhance CE.¹⁴⁻¹⁵ While several research groups used laser light pairs in SMF's to achieve the maximum signal to noise ratio, the highest CE is required.^{1, 16}

In this paper, we propose a new scheme that combines single mode solid core fibers (SMSCF) with a coated plano-convex lensed (CPCL). The theoretical background on SMSCF and their alignment is explained, and then the Gaussian intensity distribution of the laser and its diameter as a function of distance is simulated for efficient mode matching. The fiber coupling efficiency (FCE) was demonstrated in the SMSCF with a 9 μ m core diameter, resulting in a high efficiency. However, neither theoretically nor experimentally, tapering strategies and tolerance analysis have yet to be addressed at mode field transmission. In the optical system, structural, optical property, experimental, and modeling data must also be explored in more depth. As a result, we present the effect of loss in the coupling efficiency estimate for potential optoelectronics applications in this paper. The theoretical fiber coupling efficiency (FCE) was simulated with specified parameters in addition to being achieved experimentally.

This article belongs in the following category: The first section provides some background information on the basic theories relating to coupling loss and the motivation for work on SMFs. Section 2 discusses the SMF coupling principle in the context of the SMF-CPCL coupling scheme theory. Section 3 discusses the structure and performance of optical fiber coupling efficiency (theoretical analysis), Section 4 discusses our experimental verification and results analysis, and Section 5 concludes with a brief overview and conclusion. Finally, we present a forecast of development prospects, as well as our relevant observations and perspectives.

2. Principle And Various Structure Of Cpcl-smscf

Optical fiber lensing schemes have been addressed as one of the most essential processing approaches, and all the phenomena required to grasp the optical fiber lensing scheme are depicted in Fig. 1. Because the laser beam in a free space optical communication (FSOC) link travels a considerable distance, we envision it as plane waves entering the receiving terminal. E_α is the laser light field at the pupil plane α , while E_0 is the light field on the focal plane O after light wave passes through the CPCL, E is the laser light field at the pupil plane. By developing a more efficient coupling model of optical systems, the effect of various parameters on the FCE is investigated. A lensed equation ($f = R/n-1$, where n is the index of refraction and R is the radius of curvature of the lens surface) can be used to compute the focal length of each CPCL.^{17–19} When the light source's area is smaller than the core's, a lensed system is utilized to connect the source and the optical cable. The lensing strategy enhances the FCE in SMFs based on the given properties.

The wavelength of the laser was 632.8nm, the focus CPCL diameter was 25mm, the focal length was 25.4mm, and the SMFs mode field radius was measured in micrometers. Figure 2 shows the simulation curve for the FCE of the SMFs with the fiber radial offset. Because we employed lenses with focal lengths of 25.4 and diameters of 25 correspondingly, the distance between the CPCL and SMFs had an essential influence in establishing the laser beam size. We have also demonstrated a coupler laser into the SMF's, it consists of three steps, first is to fixed the translation stage, the second step is to aligned the incoming beam on the back-propagation of alignment beam into the location, the third step is to optimizing the coupling and using the techniques. The greatest angle of incidence for which entire internal reflection can

occur inside the fiber must be maintained. The light source's pattern will be suitably linked.²⁰⁻²¹ The fiber mode field was used by several other researchers to be combined with Gaussian, not J/K.²³⁻²⁴

$$F_o(r, \vartheta) = \sqrt{\frac{2}{\pi \omega_o^2}} \exp(-r^2 \omega_o^{-2}) \dots\dots\dots 1$$

Where (r, ϑ) shows the polar coordinates (PC) of a particular point in the focal plane O. ω_o is the mode-field radius of SMFs. For a laser cavity such as He-Ne laser was used in the laboratory, the waist is located roughly at the exciting lens. ω_o is related to ω by

$$Fa(r, \vartheta) = \sqrt{\frac{2}{\pi \omega_a^2}} \exp(-r^2 \omega_a^{-2}) \dots\dots\dots 3$$

And

$$\omega_a = \frac{\lambda f}{\pi \omega_o} \dots\dots\dots 4$$

Where ω_a is the radius of back propagated optical fiber mode field radius, f is the focal length of the coupling lens, and λ is wavelength of HeNe laser which is used in the experiment. Most notably, increasing or decreasing the distance between the CPCL and SMFs can have a major impact on performance. Because the mode field radius of single mode fibers (SMFs) is too short and only fundamental mode transmission is permitted in SMFs, the filtering effect of a spatial filter with a radius of ω_o placed at the focus on the optical field E_o can be considered when considering the method of plane wave coupling into SMFs through the focusing CPCL. The silica thickness is one or several orders of magnitude less than the fiber core diameter, as seen in Table 1. Indeed, the latest nested core fibers enable low attenuation wide bandwidth ranges, SM transmission on core regions, and relative long-distance propagation up to 10km.³⁷

Table 1. Parameter in various single mode solid optical fibers.

Types	Core Diameter	Thickness	Transmission loss	Reference
Densely Arrangements	$\sim 46\mu m$	$0.51\mu m$	300dB/Km	28
	$\sim 50\mu m$	$0.28\mu m$	180dB/Km	29
	$\sim 60\mu m$	$1.4\mu m$	17dB/Km	30
Nested	$\sim 25\mu m$	$2.3\mu m$	75dB/Km	31
Suspended	$\sim 33\mu m$	$\sim 0.78\mu m$	2dB/Km	32
Tube	$\sim 35\mu m$	$\sim 0.5\mu m$	6.6dB/Km	33
Suspended	$\sim 30\mu m$	$0.44\mu m$	180dB/Km	34
Capillary	$\sim 30\mu m$	$0.83\mu m$	30dB/Km	35
Tube	$\sim 41\mu m$	$0.545\mu m$	7.7dB/Km	36

2. Experimental Setup

The model and parameters of the kit used in the experiment are listed below. For altering the power of the Gaussian beam, we employed a 632.8 nm collimated laser source with half λ in front of it. The newton ring was made with two keyholes for effective mode matching with the optical fibers. To narrow the beam to the tip of the fiber's core, a fixed and adjustable lens (CPCL-truncated sphere) collimator (THORLABS LA1252-B and N-BK7B, respectively) was utilized. When light passes through the lens (CPCL), it is directed into the SMFs by this lens. We also employed a 1.5-meter single-mode fiber (SMF-HI1060), which is an optical fiber designed to carry only one mode of light (with mode field diameter). The mode-field diameter of the SMF utilized here is 9 meters, the cladding diameter is 125 meters (SMF Numerical Aperture 0.12), and the bandwidth is extremely high (1000 MHz). According to theoretical estimates, the CE increased as the fiber NA grew. The SMSCF and FCE computations are done with the detector. In order to better understand the formation process, the building dynamics of FCE have been examined utilizing a variety of theoretical and experimental methodologies. The phenomenon of total reflection is exploited in fiber optics because the amplitude is not lowered in total internal reflection. Figure 3 shows a schematic representation of the coupling efficiency setup.

To simulate laser light propagation in SMFs, we created a numerical model for light propagation into optical fibers. This work will cover the unknown FCE knowledge in optical fibers and will provide the literature with the missing theoretical evidence for the coupling. Furthermore, experimental researchers would be motivated to further examine this critical propagation beam and coupling for future laser applications. Additionally, SMSCF also used for sensing, when a well define polarization of laser light is needed at a remote sensing point.

3. Theoretical Analysis

The most crucial thing to do to make the FCE computation reliable is to describe the law of laser light transmission across optical fibers. Eq. 5 can be used to derive the propagation characteristic in the SMSCF propagation model.²²

$$V = K_f a (\text{NA}) \dots\dots\dots 5$$

The V number can be used to characterize which guided modes are allowed to propagate in an SMF's, where K_f is a free space between numbers of modes in an SMF's, "a" is the radius of the core, and NA is the numerical aperture of the optical fibers. A theory for the calculation of the spherical aberration losses of CPCL is presented; the aberration loss is calculated as a function of the parameter. A 632.8 nm uniform wave laser beam is supplied to a fast-steering lens (CPCL), which is used by a focusing lens; a laser component, to inject centered and coupled light into an SMF. The following expression gives the theoretical coupling efficiency (CE) parameters. Mode matching solution for coupling an elliptical Gaussian beams with axial off set 'D' the CE is as follows.

$$T = \frac{\frac{4w^2}{\omega_x \omega_y}}{\sqrt{\left(1 + \frac{\omega_{fiber}^2}{\omega_x^2}\right) 2 + \frac{k^2 w^2}{4R_x^2}} \sqrt{\left(1 + \frac{\omega_{fiber}^2}{\omega_y^2}\right) 2 + \frac{k^2 \omega_{fiber}^2}{4R_y^2}}} \dots\dots\dots 6$$

Where, $k = 2\pi / \lambda$

$$\omega_{x,y} = \omega_{x_0 y_0} \left(\frac{1}{\sqrt{1 + \frac{\lambda^2 D^2}{\pi^2 w^4}}} \right) \dots\dots\dots 7$$

$$R_{x,y} = D \left[1 + \left(\frac{\pi \omega_{x,y}^4}{\lambda^2 D^2} \right) \right] \dots\dots\dots 8$$

In Eq. 6, putting the value of ω_x , ω_y , R_x and R_y , and for mode matching, if misalignment is neglected, then only the irregular Gaussian beam of the laser needs to be matched with another circular Gaussian mode of the fiber, as shown in Eq. 6..

$$T = \frac{4\omega_{fiber}^2 \omega_x \omega_y}{\left(\omega_x^2 + \omega_f^2\right) \left(\omega_y^2 + \omega_f^2\right)} \dots\dots\dots 9$$

The incoming beam from the He-Ne laser was elliptical (rigidity) in our situation, so the incoming beam was transformed to a circular beam with the use of key-holes for perfect mode matching with the SMFs and to prevent axial offset and mode-matching limitations. We used a simple mathematical method to calculate coupling efficiency in SMFs and obtain quick calculations (in above equation we replace ω_0 by

ω_a). We employed a 632.8 nm laser with a Gaussian power density profile of 3.01mW and a beam width of $D = 2.1\text{mm}$. The coupling efficiency (CE) is calculated as follows:

$$I(r) = I_0 \exp\left(-\frac{2r^2}{\omega_0^2}\right) \dots\dots\dots 11$$

So, concerning the beam profile, the maximum FCE is different. In other words, the coupling efficiency improves whenever the beam shape is similar to the optical fiber mode.²⁵

4. Experimental Results And Analysis

The laser structure was prepared using the LZM100 laser splicing and glass processing system, which has a powerful heating system and a high-precision moment control system and can be utilized for shaping and fusion of single mode solid core fibers (SMSCF). The fiber coupling in the presence of keyholes and simulated turbulence was investigated experimentally using the CPCL (these lenses are built from RoHS-compliant N-BK7 glasses and can focus a collimated light beam from a point source). By using a lensing scheme technique, we were able to accomplish low-loss light coupling from CPCL to SMSCF (LST). To attain the high FCE in the laser cavity, the following equation was used.^{23, 25}

$$\eta = \frac{\int \int E\alpha^*(r) F\alpha(r) ds / 2}{\int \int |E\alpha(r)|^2 ds \int \int |F\alpha(r)|^2 ds} \dots\dots\dots 12$$

In recent years, research on fiber laser coupling systems has mostly concentrated on the creation of new types of optical lenses (CPCL) to improve the optical coupling performance of laser technology systems in laboratories and industry. We have noted that in the beginning slop efficiency was very small when the light passes through in SMSCF and it was 27.9% (we had output power 0.84mw was very low in term of input power) in the optical system as shown in Fig. 4 (a), as well the beam was doesn't look like a nice Gaussian beam. Typically, the beam propagation method is only used to solve for the intensity (I) and modes within the shape wave guide structures. It appeared that there could be issues at the moment, one of which is that if the FCE in the system is less than 32%, then either the beam of light is not effectively coupling into SMSCF or the mode matching solution is incorrect. Whereas, for the identical coated lens as indicated, maximum FCE was achieved by employing the GBPOP approach. The simulation results demonstrate that the coupling efficiency may be optimized by selecting a proper core fiber waist diameter (laser-output power) as shown in Fig. 4 (b, c, d, e), and a centered Gaussian beam spot has been established.

According to simulation results obtained using the beam propagation method (BPM), the coupling efficiency for SMFs with large MFDs is highest when the waist diameters are approximately 9/125 μm . The tracing software (Trace-pro) was used to simulate and calculate the power coupling efficiency communicated to the core of optical fiber, which is generally used to determine the split ratio in the coupler and the pump power in the laser system. The critical bending diameter for the basic mode, which

was calculated using the analytical solution for a hollow-core fiber (HCF), ranges from 8 to 12.8cm depending on the angle between the fiber orientation and the bending plane.²⁵

We studied the effect of bending by altering the coil bending diameter from 15 to 32.5 cm at 5 cm intervals (the input power was > 3mW). In comparison to the output power with a 32.5 cm bending diameter, the average power with a 15 cm bending diameter was reduced by 5.2%. Good beam quality is critical for consistent and high-quality material processing, whether for precision machining or laser surgery. Laser light linked into a single-mode fiber is tested for attenuation. The out beam maintains its good beam quality over the whole bending diameter as demonstrated in Fig. 4. (g). Many sensing and imaging applications require a good laser beam quality with circular symmetry and as close as possible to the fundamental transverse modes.

Setting up a good coupling model will help to improve the accuracy and processing efficiency. If the output power is less than 1mW, then it is dependent on a particular distance in optics. As illustrated in Fig. 4f, when the distance between CPCL and fiber is more than or equal to 1.8 cm, the coupling efficiency (CE) in SMFs will be significantly reduced throughout the system. Because the focal point size is dependent on the optical system and the laser's output property, the aforementioned beam spot size varies with each output power in the optical system. Whether for precision machining applications or laser surgery, a good beam with high quality is essential for reliable and high-quality material processing. The CE of 50% was obtained employing a variety of techniques²⁶, ranging from hollow-core fibers with a large core diameter to SMFs (NA of SMFs is ~ 0.22), with laser coupling efficiency of 45.43% by using a 780 nm collimated laser source.²⁶ We have found an increase in the amount of FCE during our experiment. The laser system's efficiency is 0.84mW, 1.19mW, 1.41mW, 1.69mW, and 2.045mW, respectively. At $P_{\text{out put}}=2.045\text{mW}$, a Gaussian beam can be clearly seen, resulting in a maximum coupling efficiency of $\eta_{\text{max}} = 68\%$, which was confined by the input beam with low spatial beam quality. Figure 5(a) shows the average output power as a function of pump power. With a slop efficiency of 68%, the output power increases from 0.84mW to 2.045mW. Because of the heat accumulating on the optical fibers, increasing the pump power further would result in an unstable pulse train. The inset reveals that at maximum power, the fluctuation range was only 2mW, and the root main square (RMS) power fluctuation was only 1.1mW, suggesting incredible long-term stability.

In our experiment, we found that the insertion length of the without tapered SMSCF influenced the all coupling efficiency. Here, we carry out the simulation and Fig. 5(b) shows the simulated results of the relative CE Changing with the insertion depth of the without tapered, or with clipping SMSCF. The waist diameter of the SMSCF at end set to 9 μm . In Fig. 5(b) right side, it can be seen that the CE changes periodically with insertion depth, which is due to the periodical variation of the cavity along SMSCF. The maximum change in CE even exceeds 55%. The results reveal that in order to achieve the highest CE from the CPCL to SMSCF, the insertion position needed fine adjustment. Table 2 summarizes the major SMSCF parameters assessed in this study and compares them to those recorded in other studies.

Table 2
The parameter of the SMSCF used for simulation and experiments.

Fiber Source	References	Coupling Efficiency (%)	Numerical Aperture (NA)	Core Diameter (μm)	Attenuation (α)
SMSCF	Experimental ²⁷	30%	0.16	9 μm	-
-	-	36%	0.18	9 μm	-
-	-	50% (With tapering)	0.22	9 μm , 6 μm , 3 μm	-
-	Experimental ²²	45.43%	0.12	5 μm	0.157
-	Experimental ³⁸	~47%	-	~40 μm	-
-	Experimental ³⁹	~70% (With tapering)	-	~46 μm	-
-	Present	~68% (Without tapering)	0.12	9 μm	0.143

The maximum FCE is 27%, 39%, 47%, 60%, and 68% (experimental method) when the NA of SMFs is 0.12. A coupling efficiency of 68% was achieved with a coupling unit consisting of a CPCL with a focal length of 25 mm, as illustrated in Fig. 5(c). Figure 5 (d) shows a fundamental mode distribution that fits the zero order Bessel function, the Gaussian distribution is used to approximate the Bessel function (it is utilized to determine acceptable mode field radius), and the inaccuracy produced by the alternative solution is kept to a minimum. As shown in Fig. 5 (e), the maximum FCE was achieved utilizing the GBPOP for the same N-BK7 CPCL. The influence of misalignment on FCE was also investigated by measuring FCE for coated lens tilts. The optical power is attenuated to P_{output} at the end of the optical fiber in the SMSCF. For the fiber, we define an attenuation coefficient (α).

$$\alpha = \frac{1}{L} \ln \left(\frac{P_{\text{in}}}{P_{\text{output}}} \right) \dots\dots\dots 13$$

Where L is the length of the fiber used for the input optical fibers. Thus for our case, the attenuation ~ 0.143. The theoretical prediction is one thing and getting the experimental value or results as par with it is far more complicated. It took us around 5–6 weeks to try most of the possible combinations of the CPCL system and at last with a fair amount of perseverance we were able to couple into the fiber,

$$P_{\text{out put}} = 2.045\text{mW} \dots\dots\dots 14$$

This means we were able to reach the maximum FCE, in addition to the efficiency, which would have been higher if more iteration with lensed and beam size adjustments had been performed. By adjusting the

structure and coupling parameters, a high FCE and good process parameters can be achieved. The ability to launch light into optical fibers that will aid us in future experimental settings.

5. Conclusion

In order to respond to the need for coupling applications between CPCL and single mode solid core fiber, we proposed a lensing scheme to improve the efficiency of the fiber coupling from CPCL to optical fiber (FCE ~ 68%) 1.5dB loss in this paper, and the preparation process of the coupling structure was thoroughly investigated. The offset, banding, and damage of SMSCF will affect the coupling, and all of these problems need to be avoided in the following experiments for a maximum efficiency, which is hoped to be further increased by improving the performance of with tapered fiber and the coupling systems. We discovered that putting laser light into SMSCF at a right angle is a better approach to detect FCE in optical fibers. The attenuation of laser light after it has been connected into an SMSCF is measured ($\alpha = 0.143$). It also shows that the suggested theory is more accurate for designing couplers and calculating FCE than the commonly used Gaussian beam optics (GBO) that ignores spherical aberration. This work opens new opportunities for all fiber structured glass lasers, which is very significant for its future applications such as optoelectronics and sensing.

Declarations

Disclosure

The author declares no conflict of interest.

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Figures

Figure 1

Schematic illustration of the lensing scheme with special light coupling into single-mode fiber (SMF's).

Figure 2

Simulation data, relationship between the FCE and fiber offset.

Figure 3

The experimental setup for investigating the coupling efficiency η_{max} in a single-mode solid core fiber (SMSCF); Insets: (Left) Beam profile of fiber laser source, (Right) Beam profile of HI-1060 SMF output;

PM-power meter, CPCL- reflection coated plano-convex lens, D- detector using for measure the beam quality, TS- translation stage.

Figure 4

Beam delivery setup schematic; Insets: Solution of the equation (1) assuming Gaussian initial output beam profile. (a-e) snapshot of the optical beam from an SMF’s (The irradiance surface), in different propagation distance from the beam waist to the point at which the beam radius has increased to $1.4w_0$. (f) Shows that a coupling loss in the optical system versus distance. (g) Translation loss vs. bending radius.

Figure 5

(a) The output Characteristics versus the incident power and measured the slop efficiency (Maximum output power) in SMSCF by using CPCL. (b) Relative FCE changing with insertion depth of the without tapered fiber at the output end, Where the dots are the simulated results and the solid line is the fitting curve and also represent the parallel transmission light field of the SMSCF with waist diameters of $9\mu\text{m}$ at 633 nm , (c) Plot depicting the relationship between the coated lenses FCE and the lens's to source fiber

separation (start separation 1.8cm) along the optical axis. (d) The banding loss and mode field distribution of high order mode and fundamental mode at 1400nm and (e) SMSCF output beam profile.

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