



Article High-Efficiency Coupling Method of the Gradient-Index Fiber Probe and Hollow-Core Photonic Crystal Fiber

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Featured Application: Supplying a high-efficiency coupling method of the gradient-index fiber probe and hollow-core photonic crystal fiber for gas detection.

Abstract: A high-efficiency coupling method using the gradient-index (GRIN) fiber probe and hollow-core photonic crystal fiber (HC-PCF) is proposed to improve the response time and the sensitivity of gas sensors. A coupling efficiency model of the GRIN fiber probe coupled with HC-PCF is analyzed. An optimization method is proposed to guide the design of the probe and five samples of the GRIN fiber probe with different performances are designed, fabricated, and measured. Next, a coupling efficiency experimental system is established. The coupling efficiencies of the probes and single-mode fiber (SMF) are measured and compared. The experimental results corrected by image processing show that the GRIN fiber probe can achieve a coupling efficiency of 80.22% at distances up to 180 μ m, which is obviously superior to the value of 33.45% of SMF at the same distance. Moreover, with the increase of the coupling distance, the coupling efficiency of the probe is still higher than that of SMF.

Keywords: hollow-core photonic crystal fiber; GRIN fiber probe; coupling efficiency; gas sensing

1. Introduction

A hollow-core photonic crystal fiber (HC-PCF) has periodical microstructures of air holes surrounding a hollow core where light is confined [1]. Because the light is trapped in HC-PCF by a photonic bandgap in the cladding that is made of spaced air holes instead of internal reflection, it is possible to guide light in a gas-filled core [2]. In addition, its long interaction length can realize resonance and near-resonance light-light and light-matter interactions [3]. Due to its excellent characteristics in gas sensing, it has been extensively studied for gas detection. To realize an all-fiber gas sensor, single-mode fiber (SMF) and HC-PCF are usually utilized for coupling, which has the advantages of a compact structure, easy miniaturization, light weight, anti-interference, and long working range [4–6]. However, the assembly of SMF and HC-PCF has a low coupling efficiency, which will reduce the output light intensity and thus reduce the sensitivity of the detection system according to Lambert-Beer law [7].

Many efforts have been made to improve the coupling efficiency. In one proposed method, the structure or fiber mode of HC-PCF [8,9] is specifically selected, or the micropore collapse effect [10] is reduced, but with limited improvement of the coupling efficiency. In another proposal, the SMF is

wedged into HC-PCF by special cutting, to ensure an ultra-high coupling efficiency [11]. However, the structure is too compact and prevents the gas from entering the HC-PCF, resulting in a poor response time of the sensor. In view of this, the coupling efficiency can only be improved by shortening the distance between HC-PCF and SMF. In order to obtain a higher coupling efficiency, HC-PCF should be as close as possible to SMF in consideration of the rapid divergence of SMF-emitted beams. By controlling the distance between SMF and HC-PCF, it is shown that the coupling efficiency is highest when the coupling length is 7.618 μ m [12]. However, due to this short distance, the gas diffuses into the HC-PCF very slowly [13], thereby reducing the response time of the sensor. Additionally, the coupling gap is difficult to control for such a short distance.

In view of this, a coupling method that can achieve a high coupling efficiency at a long coupling distance is proposed. By adding a GRIN fiber probe to the SMF, the coupling efficiency can be substantially improved over the desired coupling distance. Compared to the all-fiber structure for gas detection using a GRIN lens with a large volume [14], a GRIN fiber probe is an all-fiber optical lens composed of a single-mode fiber, no-core fiber (NCF), and GRIN fiber. It has an ultra-small structure size and good focusing performance [15]. It has been widely used in the field of optical coherent tomography (OCT) [16–18] and interference sensing measurement [19,20]. The light emitted from the GRIN fiber probe has the characteristics of focusing first and then diverging, which can obtain a smaller beam waist spot at a longer distance, thus overcoming the shortcoming of the short working distance of SMF. This excellent characteristic can be used in the study of HC-PCF gas sensors: a smaller beam waist size helps to improve the coupling efficiency of the probe and HC-PCF, while a longer working distance can maintain a long gap between the two, which is conducive to the entry of gas into HC-PCF, improving the response time of the sensor.

2. Coupling Model of the GRIN Fiber Probe and HC-PCF

The GRIN fiber probe is an all-fiber optical lens which is fused by a single-mode fiber, no-core fiber, and GRIN fiber in turn. The coupling model of the HC-PCF and GRIN fiber probe is shown in Figure 1.



Figure 1. Coupling model of the GRIN fiber probe and HC-PCF.

Symbols are set as follows: λ is the light of the wavelength and ω_0 is the beam radius of the Gaussian beam, the refraction index of the NCF is n_0 , the length of the NCF is L_0 , the GRIN fiber lens has the refractive index in the center n_1 and the gradient constant g with length L, the refractive index of the transmission medium in the application environment is n_2 , and z is the coupling distance or gap width between the GRIN fiber probe and HC-PCF.

If light has no energy loss in the optical fibers, the working distance z_{ω} and focusing spot size $2\omega_f$ of the GRIN fiber probe are expressed as [21]

$$z_{\omega} = \frac{S_1 \cos(2gL) + S_2 \sin(2gL)}{S_0 - S_3 \cos(2gL) - S_4 \sin(2gL)}$$
(1)

where $S_0 = n_1^2 g^2 + n_1^2 g^2 L_0^2 a^2 + n_0^2 a^2$, $S_1 = -2n_0 n_2 L_0 a^2$, $S_2 = n_1 n_2 g + n_1 n_2 g L_0^2 a^2 - n_2 n_0^2 a^2 / (n_1 g)$, $S_3 = n_1^2 g^2 + n_1^2 g^2 L_0^2 a^2 - n_0^2 a^2$, $S_4 = 2n_0 n_1 g L_0 a^2$, $a = \lambda / (n_0 \pi \omega_0^2)$;

$$2\omega_f = 2\omega_0 \sqrt{P_0 \cos^2(gL) + P_1 \sin^2(gL) - P_2 \sin(2gL)}$$
(2)

where $P_0 = 1 + a^2 (L_0 + n_0 z_\omega / n_2)^2$, $P_1 = z_\omega^2 n_1^2 g^2 / n_2^2 + a^2 (n_0 / (n_1 g) - n_1 z_\omega L_0 g / n_2)^2$, $P_2 = z_\omega n_1 g / n_2 - a^2 (L_0 + n_0 z_\omega / n_2) (n_0 / (n_1 g) - n_1 z_\omega L_0 g / n_2)$.

 $\omega(z)$ is set as the radius of the beam from the GRIN fiber probe at distance z and can be given as

$$\omega(z) = \omega_f \sqrt{1 + \left[\frac{\lambda(z - z_\omega)}{\pi \omega_f^2}\right]^2}$$
(3)

The power of emitted light from the GRIN fiber probe is set to p_0 . To avoid a large number of complex calculations for coupling efficiency using an overlap integral [22], a simplified model that only takes distributions of the input beam into consideration is adopted. The emitted light from the GRIN fiber can be approximated as a Gaussian beam, so the power received at the receiving end can be expressed as

$$p_t(z) = \int_0^{\frac{d}{2}} \frac{2p_0}{\pi\omega^2(z)} \exp(-\frac{2r^2}{\omega^2(z)}) 2\pi r dr$$
(4)

where *d* is the mode field diameter (MFD) of HC-PCF. From Equations (3) and (4), the coupling efficiency of the GRIN fiber probe coupled with HC-PCF can be expressed as

$$\eta = \frac{p_{\rm t}}{p_0} = 1 - \exp(-\frac{d^2/2}{\omega_f^2 + \left[\frac{\lambda(z - z_\omega)}{\pi\omega_f}\right]^2})$$
(5)

As a comparison, the spot size of the Gaussian beam after it is emitted from SMF [12] is

$$\omega(z) = \omega_0 \sqrt{1 + \left[\frac{\lambda z}{\pi \omega_0^2}\right]^2} \tag{6}$$

and the SMF coupling efficiency is expressed as

$$\eta' = \frac{p_{\rm t}}{p_0} = 1 - \exp(-\frac{d^2/2}{\omega_0^2 + \left[\frac{\lambda z}{\pi \omega_0}\right]^2}) \tag{7}$$

Comparing Equations (5) and (7), the coupling efficiency of the GRIN fiber probe coupled with HC-PCF in Equation (5) achieves the maximum value when the coupling distance z is equal to the working distance z_{ω} of the probe, while the coupling efficiency of SMF coupled with HC-PCF in Equation (7) achieves the maximum value when z is equal to zero; that is, a GRIN fiber probe can focus an emitted spot at the working distance of the probe when the maximum coupling efficiency is achieved, while SMF achieves the minimum spot and maximum coupling efficiency at zero distance. As a result, the GRIN fiber probe achieves a higher coupling efficiency at a longer distance, which demonstrates the superiority of the GRIN fiber probe over SMF when coupled with HC-PCF.

When the coupling distance *z* between the GRIN fiber probe and HC-PCF is equal to z_{ω} , Equation (5) shows that the maximum coupling efficiency is only related to the waist radius ω_f . If γ is set as the ratio of the waist diameter of the GRIN fiber probe to the MFD of HC-PCF $2\omega_f/d$, the maximum efficiency can be expressed as

$$\eta = 1 - \exp\left[-2\left(\frac{1}{\gamma}\right)^2\right] \tag{8}$$

The coupling efficiency η becomes a function of the ratio γ , and it is necessary to analyze the relationship between the two. If the waist diameter is much smaller than MFD of HC-PCF, higher order modes with higher transmission losses are excited and the simplified model may not

suitable. The minimum γ is set to 0.9 and changed from 0.9 to 2.5. The corresponding coupling efficiency is shown in Figure 2.



Figure 2. Theoretical coupling efficiency η versus γ .

It can be concluded from Figure 2 that the coupling efficiency is 27.4% when the ratio γ is 2.5, and the coupling efficiency will gradually increase as the ratio decreases. When the ratio is 1, the coupling efficiency reaches 86.5%, and the coupling efficiency reaches 91.5% when the ratio is 0.9. The results show that reducing the waist radius helps to improve the coupling efficiency.

3. The Relationship between Waist Radius and Working Distance of the Probe

Figure 2 shows that the smaller the waist radius ω_f of the GRIN fiber probe is, the higher the coupling efficiency is. However, Equation (8) is based on the premise that the coupling distance between the probe and HC-PCF is equal to the working distance z_{ω} of the GRIN fiber probe. Because of this, it is necessary to analyze the relationship between the waist radius and working distance. According to Equation (1) and Equation (2) and previous studies [18–20], the nonlinear relationship between the waist radius ω_f and working distance z_{ω} is complex. Both of them are related to the structural parameters of the GRIN fiber probe, such as the length L_0 of the no-core fiber and the length L of the GRIN fiber.

With the length of GRIN fiber increasing, the working distance and waist radius of the probe change periodically, while both of them become larger with the increase of the length of the no-core fiber. On one hand, to obtain a longer working distance and smaller waist radius, the length of the no-core fiber should be weighed. Reference [21] pointed out that the length of the no-core fiber should not be too long, otherwise the light beam may exceed the inner diameter of the GRIN fiber, which makes the beam enter GRIN fiber cladding and reduces the spot quality. The maximum length L_{0max} of the no-core fiber can be calculated when the parameters of the fibers and beam are known. On the other hand, due to the periodicity pitch characteristics of the GRIN fiber, analysis of the first cycle is enough, so the length of the GRIN fiber can be limited to the first cycle L_{max} . However, previous works have not studied how to design the length of fibers to ensure the longest working distance of the probe at a specified waist radius. In view of this, an optimization solution was proposed to guide the design of the probe.

For a probe with a specified waist radius ω_f , more than one set of no-core fibers and GRIN fibers (L_0 , L) is satisfactory because of the periodic property of the function. The set that can generate the largest working distance needs to be identified. The problem above can be summarized as finding the optimal solution (L_0 , L)_{opt} from all sets (L_0 , L)_m that satisfy a specified waist radius in Equation (2), where the

optimal solution can acquire the longest working distance $Max(z_{\omega})$ in Equation (1). The problem can be converted to an optimization problem:

$$z_{\omega} = \frac{S_{1} \cos(2gL) + S_{2} \sin(2gL)}{S_{0} - S_{3} \cos(2gL) - S_{4} \sin(2gL)}$$
s.t. $\omega_{f} = \omega_{0} \sqrt{P_{0} \cos^{2}(gL) + P_{1} \sin^{2}(gL) - P_{2} \sin(2gL)}$

$$0 < L < L_{max}$$

$$0 < L_{0} \le L_{0max}$$
Max (z_{ω})

$$(9)$$

4. Fabrication and Measurement of GRIN Fiber Probe Samples

To study the coupling efficiency of a GRIN fiber probe coupled with HC-PCF further, and to demonstrate the relationship between the waist radius and working distance of a GRIN fiber probe, GRIN fiber probe samples that meet requirements should be fabricated first. Following the fabricated steps of an ultra-small GRIN fiber probe in the author's research group, samples can be fabricated and measured using the fabricated system and measuring system [21]. The measuring system is the Beam Analyzer produced by Duma Optronics, which has a beam width/position resolution of about 1 μ m with a position accuracy of ±15 μ m and power resolution of about 0.1 μ W with a power measurement accuracy of ±10%.

The parameters of materials are as follows. The center wavelength λ of the light source beam is 1.55 µm, and the SMF core radius ω_0 is 4.5 µm. The no-core fiber has a refractive index n_0 of 1.486. The 50/125GRIN fiber core has a core diameter of 50 µm, outer diameter of 125 µm, refractive index n_1 at the axis of 1.497, and gradient constant g of 5.587 mm⁻¹. The selected no-core fiber and GRIN fiber are both produced by Prime Optical Fiber Corporation (POFC). The refractive index n_2 of air is set as 1. The max length of L_{max} and $L_{0\text{max}}$ can be calculated as 0.57 mm and 0.29 mm, respectively, according to Section 3 under these parameters. NKT Photonics' HC19-1550-01 hollow core photonic crystal fiber with a mode field diameter of 13 µm is used. Five probes with different waist radii ω_f were designed and fabricated.

Theoretical and experimental parameters of the fabricated probes are shown in Table 1. The data of No. 1~No. 5 in Table 1 is the theoretical value. The corresponding length of the no-core fiber L_{0opt} and length of the GRIN fiber L_{opt} can be calculated for each γ according to Equation (9). The specified lengths of no-core fibers and GRIN fibers were cut as calculated above and the actual length of fibers was recorded in No. 6~No. 10. After that, GRIN fiber probe samples were fabricated with these cut fibers added to SMF using the fabricated system and the beam of these samples was analyzed by the measuring system. Then, the measured working distance z_{ω} and the probe waist radius ω_f were recorded in Table 1 from No. 6~No. 10.

Types	No.	γ	(L_0) opt (mm)	(L) _{opt} (mm)	ω_f (µm)	$Max(z_{\omega})$ (mm)
Theoretical results	1	0.62	0.290	0.213	4.00	0.165
	2	0.92	0.290	0.171	6.00	0.278
	3	1.23	0.290	0.151	8.00	0.376
	4	1.54	0.290	0.139	10.00	0.463
	5	1.85	0.290	0.131	12.00	0.538
Experimental results	6	0.95	0.290	0.213	6.15	0.188
	7	1.35	0.290	0.171	8.80	0.270
	8	1.56	0.290	0.151	10.14	0.320
	9	1.82	0.290	0.139	11.80	0.400
	10	2.33	0.290	0.131	15.16	0.530

Table 1. Parameters of the GRIN fiber probe with a specified waist radius.

The data in Table 1 shows that the actual waist radius and working distance of the probe are slightly different from the theoretical calculation. These errors may come from the error of the measuring device, the limitation of the fabrication device, and human operation error.

5. Coupling Efficiency Experiment and Discussion

To measure the coupling efficiency of the GRIN fiber probe and HC-PCF, an experimental system was built to test the probes above. Both the GRIN fiber probe and HC-PCF are fixed in a V-type groove of micro-displacement platform. The coupling distance between two fibers can be adjusted by a micro-displacement platform. An amplified spontaneous emission (ASE) laser is used as the light source for the GRIN fiber probe and Beam Analyzer is used as a detector to measure the power of emitted light from HC-PCF. The schematic of the experimental system is shown in Figure 3.

ASE-C-11-G of HOYATEK Company was adopted as the ASE light source, which has a central wavelength ranging from 1527 nm to 1565 nm. We selected HC19-1550-01 of NKT Photonics Company as HC-PCF. This fiber has a core radius of 10 μ m, outer cladding diameter of 115 μ m, and attenuation <0.03 dB/m. We cut 5 cm of this fiber for the experiment to reduce the effect of attenuation. XYZW76H-25-0.25 and MGA2 micro-displacement platforms of Shanghai Lianyi Company were used to adjusted the coupling distance between the two fibers, which can achieve a resolution of 1 μ m displacement within 25 mm in the direction of the measurement axis. The experimental system setup is shown in Figure 4a and the detail of the coupling part marked with a red frame is shown in Figure 4b.



Figure 3. Schematic of the experimental system.



Figure 4. Coupling efficiency testing system: (a) Experimental system setup; (b) detail of coupling part.

As shown in Figure 4a, the GRIN fiber probe connected to the ASE laser was mounted in the V-groove of the micro-displacement platform, and the emitted power p_0 was detected by the Beam Analyzer. After that, the GRIN fiber probe and HC-PCF were installed according to the assembled method in Figure 4b. The micro-displacement platform was adjusted to align two fibers until the emitted power received by the Beam Analyzer was at the maximum.

The micro-displacement platform fixed with HC-PCF was moved from the position where the distance between the GRIN fiber probe and HC-PCF was zero to 1 mm at intervals of 10 μ m. The emitted power p_t at each position was measured five times and the average value was used as the result. As a comparison, the coupling efficiency between SMF and HC-PCF was also measured following the same procedure as above by replacing the GRIN fiber probe with SMF.

In fact, the start position can only make two fibers as close to each other as possible, but the distance cannot be zero. It is difficult to tighten two fibers completely because it is likely to damage the porous structure of HC-PCF. Therefore, coupling distance correction of the result is necessary. We used a $40 \times$ magnifying glass to take pictures at the start position and measured the initial distance by image processing. The image processing is shown in Figure 5.



Figure 5. Initial distance measurement between the GRIN fiber probe and HC-PCF: (**a**) original image, (**b**) binarization processing, and (**c**) image in pixels.

Figure 5a is an original image taken by means of a magnifying glass. We extracted the pixel value in a black channel and adopted binarization processing, and the result is showed in Figure 5b. The detail in pixels marked with the frame is shown in Figure 5c. The outer diameter of 125 μ m of the GRIN fiber probe that has a clear outline is used as the reference to calculate the initial distance. The initial distance between the two can be calculated as 125*14/21 μ m, which is about 80 μ m. The initial distance in a comparison experiment that used SMF is processed in the same way.

To avoid accumulative error due to the fabrication errors in Table 1, the actual waist radius and working distance of GRIN fiber probes from No. 6~No. 10 were used as the input for calculation. The theoretical coupling efficiency of the GRIN fiber probe with a ratio γ of 0.95 according to Equation (5) and the experimental results that have been corrected are shown in Figure 6. The theoretical and experimental results of the SMF fiber are plotted in this figure as a comparison.



Figure 6. Theoretical and experimental values of coupling efficiency.

It can be seen from Figure 6 that the trend of experimental results is consistent with the theoretical results, but there is little discrepancy between the experimental and theoretical results due to some sources of error. The biggest reason for the discrepancy is that the simplified model only takes distributions of the input beam into consideration, without the distributions of HC-PCF. The second

reason is that the MFD of HC-PCF is used as the integral range and the contribution of other areas within the core diameter is neglected. Fresnel reflection, operating error, and straightness error of micro-displacement can also cause deviation.

Figure 6 shows that the coupling efficiency of the probe is lower than that of SMF when the coupling distance is less than 0.1 mm. However, with the increase of coupling distance, the coupling efficiency of SMF decreases gradually, while the coupling efficiency of the probe shows a trend of increasing first and then decreasing. The coupling efficiency of the GRIN fiber probe reaches a maximum value of 80.22% at 180 μ m, where the coupling distance is equal to the working distance of the probe, which corresponds to the theoretical calculation in Equation (5). As a comparison, the coupling efficiency of SMF at the same position has decreased to 33.45%. With the increase of coupling distance, the probe can obtain a higher coupling efficiency than SMF and gain a similar value when the distance is longer than 0.8 mm. Considering this, the incident end of HC-PCF can be placed at the range of 0.1 mm to 0.8 mm for this GRIN fiber probe, where the GRIN fiber probe can acquire a higher coupling efficiency than SMF when it is coupled with HC-PCF for gas sensing.

The experimental results show that the coupling model of the GRIN fiber probe can have a much longer working distance than SMF, so a larger gap between two coupled fibers can be achieved. The larger gap may make it easier for gas to enter the HC-PCF, so it takes less time to let the gas fill the HC-PCF before measurement, thereby reducing the system response time. In addition, the model of the GRIN fiber probe can obtain a higher coupling efficiency at the same distance, which can improve the sensitivity of the system. The higher coupling efficiency of the model means the light entering HC-PCF has a higher power, and the power of the output light from HC-PCF passing through the gas is proportional to the power of input light if the gas concentration is constant according to Lambert-Beer law. Therefore, the model of the GRIN fiber probe may display a bigger change in light power than the model of SMF when the concentration changes the same value; that is, the model of the GRIN fiber probe has a higher sensitivity.

The optimization problem used to obtain the maximum working distance for each specified waist radius is proposed in Equation (9). To verify the relationship between the working distance and maximum coupling efficiency, the coupling efficiency experiments for five fabricated fiber probes in Table 1 have been conducted. Theoretical and experimental results are plotted in Figure 7 and measurement errors are shown as error bars.



Figure 7. Theoretical and experimental working distance and maximum coupling efficiency versus γ .

The maximum coupling efficiency in Figure 7 is slightly different from theoretical value due to similar errors in Figure 6, and the working distance of the probe is slightly less than the theoretical value because of some errors expounded in Section 4. The results show that the maximum coupling efficiency of the probe decreases and the working distance of the GRIN fiber probe increases with the

increase of the coupling distance; that is, the maximum coupling efficiency and working distance are contradictory. Both of them should be balanced according to the application and the optimal choice should be studied in further experiments.

6. Conclusions

A coupling model of the GRIN fiber probe and HC-PCF has been established and a method to calculate the coupling efficiency of the model has been deduced. An optimization problem was proposed as a guideline for the design of the probe to obtain the longest working distance at a specified waist radius. A series of specified probe samples were fabricated and a coupling efficiency experiment was carried out. Image processing was implemented before the experiment to correct the results. In addition, the relationship between the coupling efficiency and working distance was discussed. The theoretical and experimental results show that the maximum coupling efficiency of the probe is obtained when the coupling distance is equal to the working distance of the probe. Although the coupling efficiency of the GRIN fiber probe at a very short distance is lower than that of SMF, the coupling efficiency of the probe is obviously higher than that of SMF with the increase of coupling distance. Therefore, the probe coupled with HC-PCF can obtain a higher coupling efficiency at a longer distance. The longer distance can improve the response time of the system and the higher coupling efficiency can improve the sensitivity of the system. Because of the contradictory relationship between the maximum coupling efficiency and the working distance of the GRIN fiber probe, some theoretical and experimental analyses are necessary in the future to select the optimized GRIN fiber probe for gas sensing.

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