Thin gas cell with GRIN fiber lens for intra-cavity fiber laser gas sensors

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ABSTRACT

Fiber laser gas sensors based on the intra-cavity absorption spectroscopy require the use of gas cells. We propose a simple and reliable gas cell using graded-index fiber lens (GFL) based all-fiber collimator. Conventional gas cells usually utilize direct fiber-to-fiber coupling without collimators or graded-index (GRIN) lens as collimators. Direct fiber-to-fiber gas cell has simple configuration, but it suffers from high coupling loss and stray light interference. Gas cells applying fiber pigtailed GRIN lens are advantageous to achieve low coupling loss. However, fiber pigtailed GRIN lens requires accurate and complicated alignment and glue packaging which could compromise long term reliability and thermal stability. The proposed technique fabricates all-fiber collimators by simply splicing a short section of graded-index fiber to single mode fiber which is both compact and durable. With that collimator, the gas cell can be fabricated very thin and are suitable for extreme environments with high temperature and vibration. In this paper, we have carried out experiment and analysis to evaluate the proposed technique. The coupling efficiency is studied versus different GFL gradient parameter profiles using ray matrix transformation of the complex beam parameter. Experiments are also done to prove the practical feasibility of the collimator. The analysis indicates that gas cell using GFLs can overcome the disadvantages of traditional design; it may replace the conventional gas cells in practical applications.

Keywords: Gas cell, GRIN fiber lens (GFL), all-fiber collimator, coupling loss

1. INTRODUCTION

In recent years, various kinds of fiber gas sensors reported are mainly based on intra-cavity absorption technology by inserting a gas cell into the laser cavity, which has been demonstrated that the sensitivity of measurement can be greatly enhanced. Although plenty of work has been done to improve the performance of the gas sensor, little attention was paid to the design of the gas cell. Gas cell is one of the most critical parts of the gas detection system, which allows the beam to interact with gas sample. The length and volume of the cell both affect the sensitivity, stability and other performances of the gas sensor. In a gas cell, the collimator is the key part, which can improve the utilization ratio of the light source, reduce the coupling loss and the interference of stray light. In commonly used gas cells, a series of lenses or GRIN lenses are always applied as the collimating components. However, accurate alignment and coupling of the lenses are complex and time consuming. Gas cells using these lenses also have poor anti-vibration reliability and thermal stability. In order to fabricate an easily coupled, low-loss and small size gas cell, a novel design utilizing GRIN fiber lens (GFL) as the collimator is introduced. With this simple-structure design, all-fiber, permanent high-strength collimator with common fiber diameter can be realized by fusing the single-mode fiber and GFL together that can not be easily damaged [1,2]. A theoretical analysis using ray matrix transformation of the complex beam parameter is investigated to evaluate the coupling loss of the gas cells. The comparison results of GFLs with different gradient parameter are given out. The analysis show that the design can have low coupling loss and small cell volume to path length ratio which means good sensitivity; experimental results about the practical feasibility of the design are also given out.

2. ABSORPTION PRINCIPLE OF INTRA-CAVITY FIBER LASER GAS SENSORS

Intra-cavity absorption spectroscopy based on the measurement of the light absorption by certain kind of material is one of the most important techniques for the gas detection. Lambert-Beer's law describes this phenomenon [3]:

$$I(\nu) = I_0(\nu)\exp(-\alpha(\nu)LC) \tag{1}$$

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Where $I_0(\nu)$ is the initial intensity of the light source, $I(\nu)$ is the intensity of the light after passing through the gas cell, C is the concentration of the gas, L is the optical path length, $\alpha(\nu)$ is the absorption coefficient of the gas. To the same kind of gas, the absorption coefficient is a constant. From Eq.1.we can get:

$$C \sim \frac{I(\nu)}{I_0(\nu)} \tag{2}$$

From the above equations, we can conclude that, if the absorption coefficient and the path length are determined, the attenuation of the light due to the absorption is relative to the concentration of the gas.

According to Eq.1, the absorbency A is proportional to C , L and $\alpha(\nu)$:

$$A = \alpha(\nu) LC \tag{3}$$

It means that the amount of the radiation absorbed is proportional to the path length. The longer the path length, the more gas will be absorbed. In principle, to detect lower concentration, we need to increase sensitivity and have large enough absorption by using longer path length.

3. DESIGN OF GAS CELL

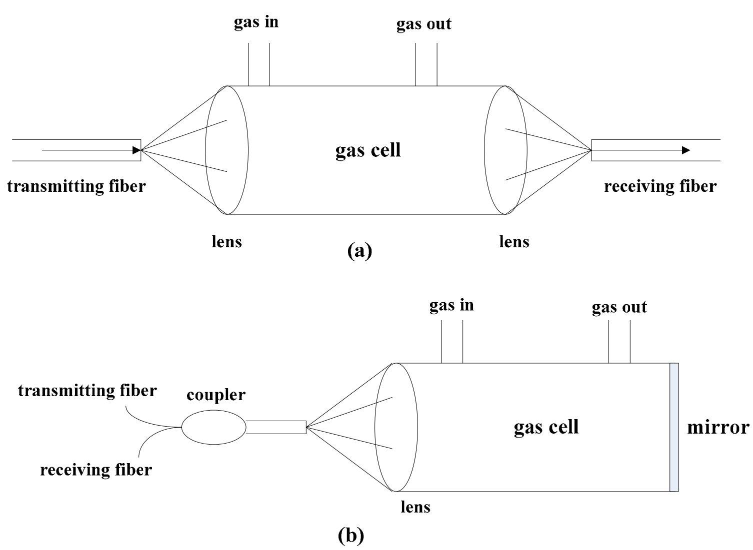

Fig.1. (a) gas cell of transmitting type (b) gas cell of reflection type

There are mainly two types of gas cells: transmission type and reflection type as Fig.1.shows [4,5]. The commonly used reflection type often employs a mirror and a series of lenses. The mirror is used to reflect the input beam and the lenses are applied to adjust the times of reflection and change the optical length. Without increasing the length of the gas cell, this structure can provide long optical path, which means the gas sample can be fully absorbed and the sensitivity can be increased. However, the complexity of the structure makes it difficult to achieve good stability and reliability. Also, the use of optical coupler to split light makes the power of the light cannot be fully utilized. The maximum output power of the reflection type is only 1/4 of the light source output power. The transmission types always combined with two graded-index (GRIN) lenses as the collimators, and can reduce the interference of the stray light. Although this structure is simpler, it still uses traditional lenses and has similar shortcomings. In order to overcome the disadvantages, GFLs is applied as the collimator instead of the lenses in our design. A GFL is a short segment of GRIN multimode fiber, whose imaging and transmitting properties are dependent on its index distribution and its length. In our gas cells, the collimator is easily fabricated by fusing GFL to a single-mode fiber with a normal splicing machine. It can be used in extreme environments with great vibration and high temperature. Due to its small size, the gas cell also has the potential for other applications. The ray analysis and the theory of collimation by GFL using the ray matrix method will firstly be described.

3.1 Ray analysis in GFL

A square-law GFL has a refractive index dependent on its radical distance, which is given by [6]:

$$n^2(r) = n_0^2(1 - g^2 r^2) \tag{4}$$

where n_0 is the refractive index along the axis, g is the gradient parameter and r is the radial distance from the axis. Fig.2. shows the refractive profile of GRIN fiber and the beam path through it [7]. As we can see, the ray path in GFL is sinusoidal profile with the period L given by:

$$L = \frac{2\pi}{g} \tag{5}$$

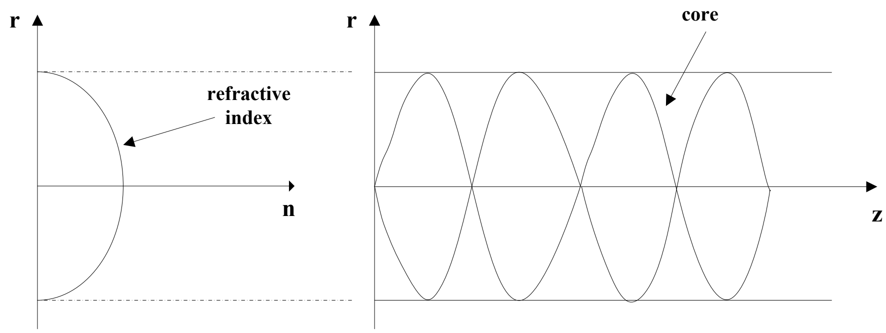

Fig.2. Refractive profile and ray path of GFL

The position and the slope of the ray traveling through GFL can be described by the ray-transfer matrix (ABCD matrix) [7, 8].

$$\begin{pmatrix} r_{out} \\ r'_{out} \end{pmatrix} = \begin{pmatrix} \cos(gz) & \sin(gz)/n_0 g \\ -n_0 g \sin(gz) & \cos(gz) \end{pmatrix} \begin{pmatrix} r_{in} \\ r'_{in} \end{pmatrix} \tag{6}$$

where z is the length of the GFL, r_{in} and r'_{in} are the position and slope of the input ray just inside GFL respectively, r_{out} and r'_{out} are the position and slope of the exit ray just inside GFL.

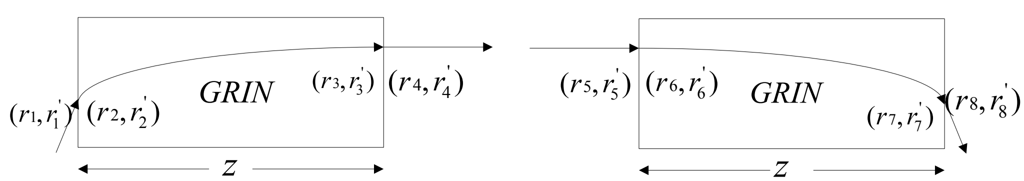

Fig.3. Path of a light beam through the transmitting and receiving GFLs

As Fig.3.shows, when one-quarter-pitch GFL is utilized, $z = l/4 = \pi/2g$. For the transmitting GFL, from Eq.6. we obtain:

$$r_4 = \frac{1}{n_0 g} r_1' \qquad r_4' = -n_0 g r_1 \tag{7}$$

The junction of the single-mode fiber and GFL can be approximated as a point light source which means $r_1 = r_2 = 0$ and further $r_4' = 0$. It reveals that the rays passing through one-quarter-pitch GFL from the axis are collimated.

For the receiving GFL, $r_5' = 0$ and further $r_7 = r_8 = 0$, which indicates that the collimated beam will converge to the axis.

Hence for a GFL, with length P given by Eq.8, the light beam will be collimated from a point light source.

$$P = (2k+1)L/4 \tag{8}$$

3.2 Design of gas cell using GFLs as the collimators

Based on the above theories, the gas cell with GFLs is shown in Fig.4. Two GFLs are spliced to the end of the single mode fibers to construct an all-fiber collimator. For this kind of gas cell, the output beam can be expressed as[4]:

$$I_1 = I_0 \eta \exp[-\alpha(\nu) LC] \tag{9}$$

where η is the loss of the gas cell including the coupling loss and other excess losses, L is the length of the gas cell.

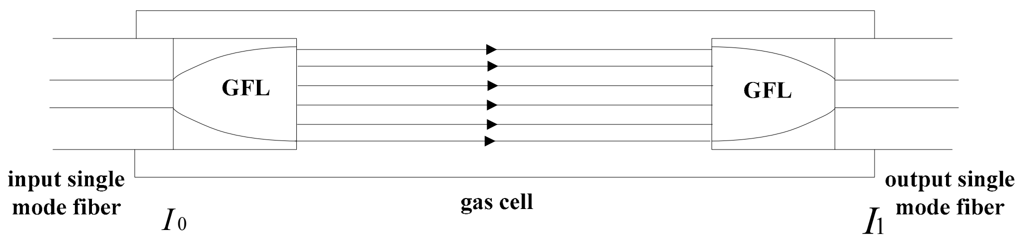

Fig.4. The configuration of the gas cell

To fabricate the gas cell, there are a number of special considerations such as suitable optical length, volume, coupling loss, etc. In theory, when the concentration of a specific gas becomes lower, enough absorbency can be achieved by increasing the path length. However, longer gas cell not only lower the minimum detection limit and increase the sensitivity, but also will reduce the received light intensity and induce higher coupling and reflection. Also, there is a limit of the cell length when the increased path length does not produce higher absorption. The gas length has relationship with gradient parameter as well. So the appropriate length of the gas cell should be determined in consideration of both the desirable lowest measurement concentration and the measurement loss.

The volume of the gas cell also affects the sensitivity of the gas sensor. Due to the small size of the GFL, the gas cell can be made very thin. The small cell volume to path length ratio makes the gas cell potential to have high sensitivity.

3.3 Coupling loss analysis of GFL

The coupling loss analysis utilizes the ray matrix transformation of the complex beam parameter. The radius of curvature of the Gaussian beam $R(z)$, the spot size $\omega(z)$ and the complex beam parameter $q(z)$ satisfy the usual relations [2]:

$$\frac{1}{q(z)} = \frac{1}{R(z)} - i\frac{\lambda}{\pi\omega^2(z)} \tag{10}$$

where λ is the wavelength of the light and n is the refractive index.

The transformation of $q(z)$ through a GFL satisfies the ABCD law:

$$q_2 = \frac{Aq_1 + B}{Cq_1 + D} \tag{11}$$

where q_1 and q_2 are the complex beam parameter in the input and output planes. From Eq.6, in combination with 1/4 pitch GFL, we obtain:

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix} = \begin{pmatrix} 0 & 1/n_0 g \\ -n_0 g & 0 \end{pmatrix} \tag{12}$$

As Fig.5.shows, the radius of the beam diverging from the GFL becomes:

$$\omega_1 = \frac{\lambda}{\pi n_0 g \omega_0} \tag{13}$$

where ω_0 is the radius of the single-mode fiber, n_0 is the refractive index at the axis.

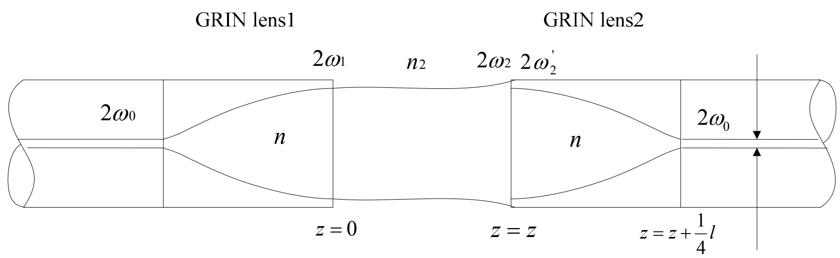

Fig.5 Propagation of a Gaussian beam through a GFL

If we assume ω_1 is the waist radius, and $n_2 = 1$ in the air, the beam radius $\omega_2(z)$ at z is[9]:

$$\omega_2 = \omega_1 \left\{ 1 + \left[\frac{z\lambda}{\pi \omega_1^2} \right]^2 \right\}^{1/2} \tag{14}$$

$$R_2(z) = z \left\{ 1 + \left[\frac{\pi \omega_1^2}{\lambda z} \right]^2 \right\} \tag{15}$$

As ω_2' is also assumed as the waist radius, we can obtain:

$$\omega_2' = \frac{\lambda}{\pi n_0 g \omega_0} \tag{16}$$

$$R_2' = \infty \tag{17}$$

The electric field emerging from GFL can be approximately assumed as Gaussian distribution and can be written in the form [10]:

$$\psi(x,z) = A(z) \exp\left[-\left(\frac{x-\Delta}{\omega} \right)^2 \right] \times \exp\left[-i \frac{k(x-\Delta)^2}{2R(z)} \right] \exp\left[-i(kz - \omega' t) \right] \tag{18}$$

where $A(z)$ is the amplitude, Δ is the transverse offset, $k = 2\pi/\lambda$, ω is the beam radius and $R(z)$ is the radius of curvature.

If there is no transverse misalignment, the mode field of ω_2 and ω_2' in Fig.5.can be expressed in the form:

$$\psi_2(x,z) = A(z) \exp\left[-\left(\frac{x}{\omega_2} \right)^2 \right] \times \exp\left[-i \frac{kx^2}{2R_2(z)} \right] \exp\left[-i(kz) \right] \tag{19}$$

$$\psi_2'(x,z) = B(z)\exp\left[-\left(\frac{x}{\omega_2'}\right)^2\right] \tag{20}$$

The on-axis coupling efficiency is determined by the overlap of the two Gaussian beams at z :

$$\eta = \frac{\left|\int_{-\infty}^{\infty}\psi_2(x,z)\psi_2'^*(x,z)dx\right|^2}{\int_{-\infty}^{\infty}\psi_2(x,z)\psi_2^*(x,z)dx\int_{-\infty}^{\infty}\psi_2'(x,z)\psi_2'^*(x,z)dx} \tag{21}$$

Combined with Eq.19.and Eq.20., we can obtain:

$$\eta = \frac{2}{\sqrt{\left(\frac{\omega_2}{\omega_2'}+\frac{\omega_2'}{\omega_2}\right)^2+\frac{k^2}{4R_2^2}\omega_2^2(\omega_2')^2}} \tag{22}$$

As a result, the coupling loss expressed in decibels, is given by:

$$L = -10\log\eta \tag{23}$$

As a comparison, if there is no GFL collimating the beam in the gas cell, as Fig.6.shows, the spot size and the curvature radius of the illumination beam along the z-axis is given by:

$$\omega_1 = \omega_0\left\{1+\left[\frac{z\lambda}{\pi\omega_0^2}\right]^2\right\}^{1/2} \tag{24}$$

$$R_1 = z\left\{1+\left[\frac{\pi\omega_0^2}{z\lambda}\right]^2\right\} \tag{25}$$

where ω_0 is the core radius of the single-mode fiber and also is the waist of the beam.

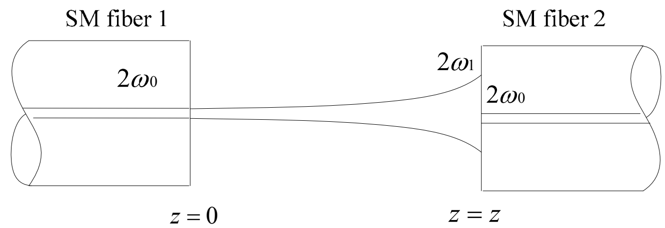

Fig.6. Propagation of light between single mode fibers

In our system, we analysis the coupling losses of four kinds of one-quarter-pitch GFLs with four different gradient parameters g_1=6.3626 mm^{-1} , g_2=4.96 mm^{-1} , g_3=2.83 mm^{-1} and g_4=1.36 mm^{-1} . The wavelength of the light source used is 1530 nm .The coupling loss is measured as a function of axial separation between the GFL ends. The relationships are shown in Fig.7.for various GFLs pairs in comparison with the coupling loss of single mode fibers. From the above formulas and the numerical simulation result, we can conclude that, the coupling loss not only depends on the separation z between the fiber ends, but also depends on the refractive index profile. GFLs with lower gradient parameters have lower coupling losses at the same axial separation.

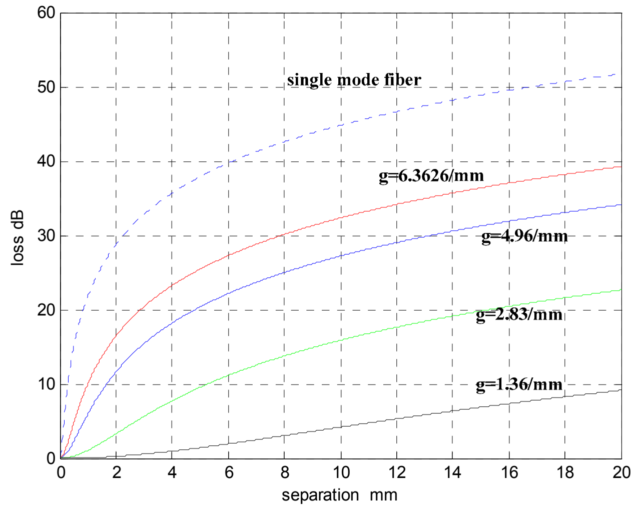

Fig.7. Coupling loss due to axis separation of different GFLs

Divergence angle is defined as Eq.26.which reflects the long-distance transmission characteristics and the concentration of the beam in space:

$$\theta = \left.\frac{d\omega}{dz}\right|_{z\to\infty} = \frac{\lambda}{\pi\omega_0} \tag{26}$$

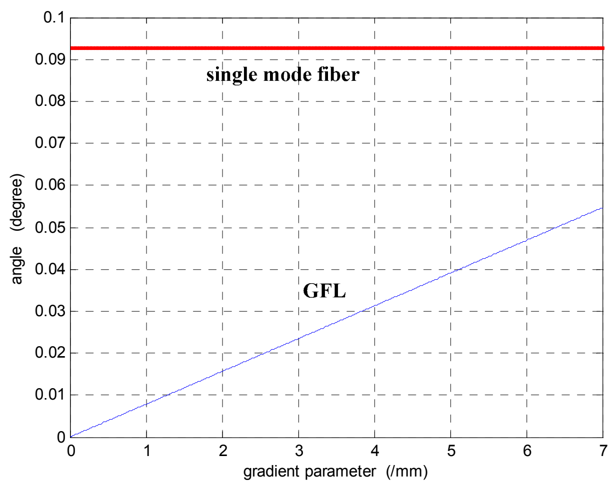

Fig.8 Divergence angles of GFLs and single-mode fiber

Fig.8.clearly illustrates the divergence angles of single mode fiber and its dependence on gradient parameter. The angle is much bigger than the one using GFL with small gradient parameter.

In order to get small divergence angle, coreless silica fibers sometimes are inserted between single mode fibers and GFL. The coreless fiber can expand the mode field of single mode fibers, provides a larger range of spot size than in a configuration without it[11]. Therefore lateral and longitudinal misalignments sensitivities can be reduced [1]. Also, due to the small size and low coupling loss of GFL, without changing the length of the gas cell, the optical length can be increased by cascading a series of GFLs together, which can highly enhance the sensitivity of the measurement.

4. EXPERIMENTAL RESULTS

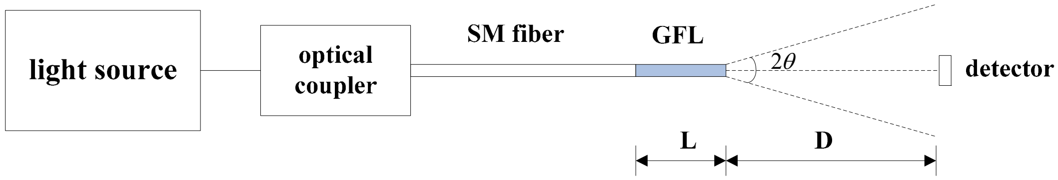

Fig.9. Experimental device

Fig.9.is the experimental device we used to measure the far-field patterns of the distribution of the diverging beam from single mode fiber and GFL respectively. The gradient parameter of the GFL is g_1=6.3626 mm^{-1} with a period length of 0.99 mm. Because the one-quarter-pitch GFL we used is less than 1 mm in length and are inconvenient for applications. Therefore longer GFLs with odds times of quarter-pitch length can be utilized. The length of the GFL we used as the collimator is 14.68 mm, approximately odd times of one-quarter-pitch length. The distance D between the detector and the end of the GFL is 75 mm.

Fig.10.gives the measurement results, the lateral axis represents the divergence angle of the basic mode field, the longitudinal axis is the normalized amplitude. The discrete points are our experimental results and the dashed lines are curve-fitted by Gaussian profiles. The fluctuations of the GFL results may due to the effect of other modes of GFL. From Eq.26.we know, the smaller the divergence angle is, the longer collimating distance and better collimating effect can be obtained. Although due to certain factors, the results of the experiments are not very exact, it still can show that the divergence angle of the GFL is much smaller than that of the single-mode fiber, which means in practical applications, the beam can be collimated by GFL, and the beam is more concentrated in space by using it.

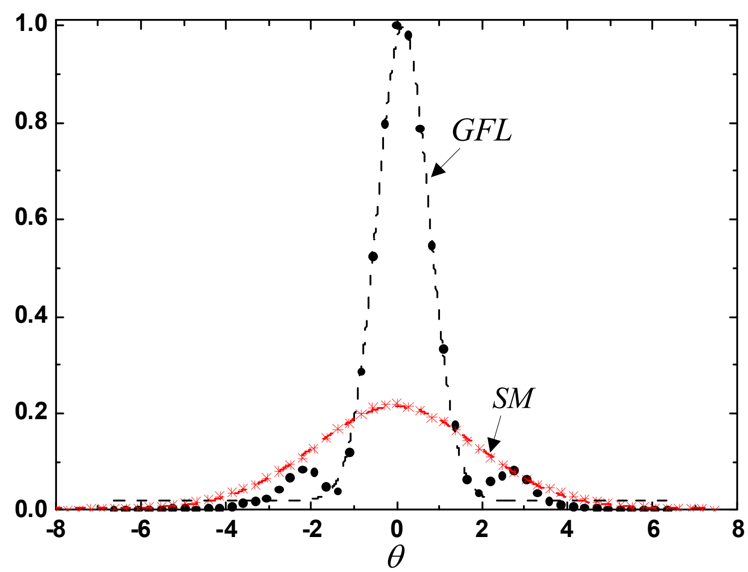

Fig.10. Far-field pattern of single-mode fiber and GFL

5. CONCLUSIONS

In this paper, a design of thin and stable gas cell with GFL as the all-fiber collimator is introduced. The advantages associated with the use of GFL includes: low loss, low cost, compact, easy alignment, common fiber diameter and stable interface by fusion. Because of its small volume to path length ratio, this design is very sensitive. The dependence on gradient parameter of coupling loss and comparisons of the coupling losses with and without GFL are given. The numerical calculation results show that, gas cell in combination with GFL has low coupling loss, and has reasonable significance in practical utilization. Experimental results indicate that the beam can be well collimated by GFL after diverging from the single mode fiber. In one word, gas cell with GFL as the collimators offers desirable application prospect and may be an alternative to the conventional design. It may also be applied in other circumstances and extend the scope of fiber-lens applications. Improvements will be done in the future work, including the following effects: core distortion at the spliced surface, the use of coreless silica fiber to expand mode diameter and other excess loss.

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