

# A compact-size D lens collimator for fiber coupling

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The paper presents a low cost and easy to fabricate compact D lens fiber optic collimator. Both the theoretical and experimental results are presented. The beam diameter and insertion loss of the lens are theoretically analyzed by using the ABCD matrix and the overlap integral methods. The experiment results show that the smallest beam diameter is found to be in the range of 380 to 400  $\mu\text{m}$  as the output distance varies from 10 to 30 mm. The insertion loss of the collimator is shown to be less than 0.3 dB. This number is slightly less than the value obtained by a conventional GRIN lens of similar dimensions for 10 to 30 mm output distance operated at  $\lambda = 1550 \text{ nm}$ .

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## 1. Introduction

Recently, the application of optical fiber communication is expanding from the trunk lines to the subscriber loops and to the local area network (LAN). In these applications, various types of low cost optical passive devices such as the power splitter, isolator, switch, add/drop module and multiplex/de-multiplex module are required. To meet these requirements, many types of fiber collimators were proposed that have attracted much attention [1-5]. The collimators are typically used to collimate the divergent light beam from an optical fiber. It

also is used to couple the light between fibers and lasers with different core diameter and numerical aperture to improve the coupling efficiency. The collimating lens used in most fiber communication has a diameter in a range of 1.8 to 2 mm. A typical fiber collimator exhibits low insertion loss and good coupling efficiency; and its unique process and high quality antireflection (AR) coating also enables collimator to handle a high power transmission. Most frequently used collimator lenses are gradient index (GRIN) lenses. However, precision in index control and the complexity in manufacture process strongly limit the mass production with high yield.

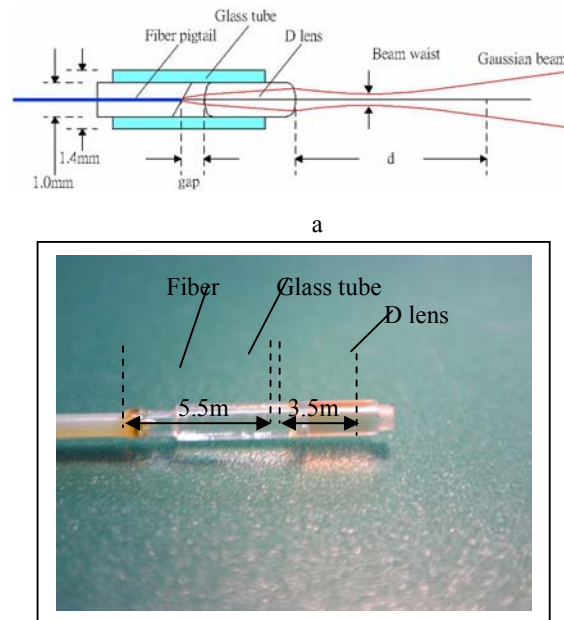


Fig. 1. (a) Schematic depicts a compact-size D lens collimator and Gaussian beam propagation from fiber tip through a D lens (b) photo taken near the D lens collimator.

In this paper we propose a compact-size D lens for fiber collimator (Fig. 1). The analytical and experimental results of the D-lens are compared with GRIN lens collimator in their optical performances. The theoretical calculations of beam propagation and insertion loss were derived using matrix transformation of the complex beam parameter (i.e. ABCD matrix and overlap integral of the beam).

## 2. Theoretical analysis

An analytical approach based on Gaussian beam propagation is used to calculate the beam diameters at different working distances [6-8]. Based on the ABCD matrix, a simple and reliable prediction is provided. The Gaussian beam propagation in the collimator system is shown schematically in Fig. 1(a). The ray matrices of the proposed collimator system based on ABCD matrix are expressed as [9]

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = M_d M_{lens} M_{gap} = \begin{bmatrix} 1 & d \\ 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} \frac{2-n_{lens}}{n_{lens}} & \frac{2r}{n_{lens}} \\ \frac{n_{lens}}{2(1-n_{lens})} & \frac{2-n_{lens}}{n_{lens}} \end{bmatrix} \cdot \begin{bmatrix} 1 & gap \\ 0 & 1 \end{bmatrix} \quad (1)$$

where  $M_{gap}$ ,  $M_{lens}$  and  $M_d$  are the ray matrices of the gap, D lens and free space, respectively,  $M_d$ ,  $d$  is the output distance from the exit lens facet, and  $M_{lens}$ ,  $n_{lens}$  is the refractive index of D lens and  $r$  is the ball radius of D lens. For the fundamental-mode Gaussian beam, the complex beam parameter,  $q_i$ , of the Gaussian beam can be written by

$$\frac{1}{q_i} = \frac{1}{R_i} - j \frac{\lambda}{\pi \cdot n \cdot w_i^2} \quad (2)$$

where  $R_i$  is the radius of curvature of the equi-phase surfaces,  $w_i$  is the Gaussian beam radius with  $i = 0, 1, 2$  or  $3$  and ( $0 = \text{input}$ ,  $1 = \text{gap}$ ,  $2 = \text{D-lens}$ ,  $3 = \text{free space}$ ), and  $\lambda$  is the wavelength of the laser beam. By taking the input beam parameter as  $q_0$ , the output beam parameter,  $q_3$ , can be expressed as

$$q_3 = \frac{Aq_0 + B}{Cq_0 + D} \quad (3)$$

where the  $A$ ,  $B$ ,  $C$  and  $D$  are the matrix elements of the ray matrix given in Eq. (1). According to the self-imaging mechanism [10], the beam waist is located at the middle of the working distance that represents the distance of two collimators at which their coupling loss is at minimum. The output beam radius  $w$  and equi-phase curvature  $R$  versus output distance  $d$  (the distance from the output facet of a collimator to the optical power) with gap = 255, 260 and 265  $\mu\text{m}$  for a wavelength of 1550 nm are calculated

and shown in Fig. 2a and Fig. 2b, respectively. Since the beam waist locates at the distance where the wave curvature  $R$ , becomes maximum, the gap between lens and fiber could be changed to determine the collimator's working distance and hence obtain the coupling efficiency and the insertion loss. In case of designing a 20mm working distance collimator, the optimum gap is 260  $\mu\text{m}$  and beam waist radius is 193  $\mu\text{m}$  at  $d = 10$  mm.

The coupling efficiency of a pair of collimators depends on the overlap integral of the beams produced by lens 1 and lens 2. Based on the derived result by Buren and Riza [10], the power transmission coefficient can be written as

$$T = \frac{4}{\frac{w_w^2(d_w)}{w_d^2(d-d_w)} + 2 + \frac{w_d^2(d-d_w)}{w_w^2(d_w)} + w_d^2(d-d_w) \cdot w_w^2(d_w) \cdot \frac{k^2}{4} \cdot \left[ \frac{1}{R(d-d_w)} - \frac{1}{R(d_w)} \right]^2} \quad (4)$$

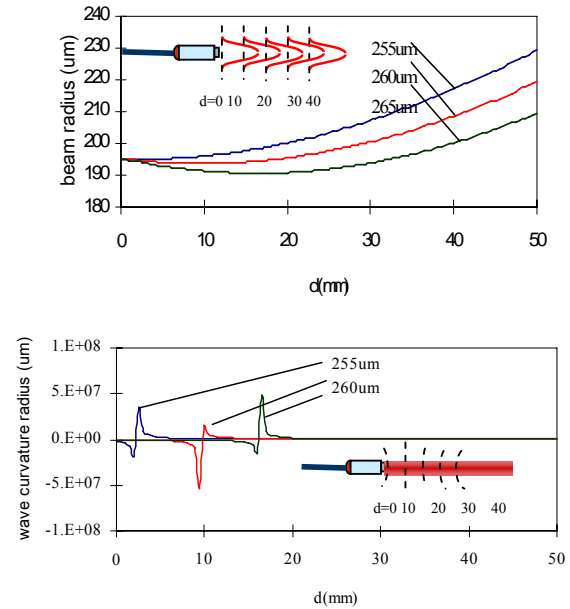


Fig. 2. (a) The theoretical calculation of beam radius  $w$  versus working distance  $d$  is shown, and (b) wave front curvature  $R$  versus working distance with gap=255, 260 and 265  $\mu\text{m}$  for wavelength 1550 nm.

where  $d_w$  is the location of beam waist,  $w_w$  is the beam waist radius,  $d$  is the output beam distance and  $w_d$  is the related beam radius, and  $R(d-d_w)$  and  $R(d_w)$  are the radii of equi-phase curves at distance  $d-d_w$  and  $d$ , respectively.  $k = 2\pi/\lambda$  is the wave number of free space. Here the power transmission coefficient is converted to the

insertion loss in unit of dB since it is commonly used in the product specification sheet of most fiber optics device manufacturers. The insertion loss is expressed as:

$$I.L. = -10 \log T \quad (5)$$

### 3. Experiments and discussion

The D lens is made of LaSF015 glass with refractive index of 1.7753 and 1.7800 for wavelength of 1550 nm and 1310 nm, respectively. The drum shape rod with a diameter of 1.0 mm is made from two D lenses grounded from 3.5 mm-diameter ball lenses (Fig. 1a). The rod was then carefully inserted into and adhered to the inner wall of the glass tube. The glass tube has a sidewall of 0.2 mm and an inner diameter of 1.0 mm. A polished 8-degree splice single mode fiber pigtail was inserted into another end of glass tube. The gap between lens and fiber pigtail was carefully adjusted using holders and micro-stages to insure that the optimal working distance is achieved. In order to reduce the Fresnel reflection between air/lenses and air/fibers interface, all lenses and the end surfaces of fibers were coated with anti-reflection layer which is made of four pairs of alternating matching layers of a quarter-wavelength thickness of  $\text{SiO}_2$  (refractive index of 1.54) and  $\text{Ta}_2\text{O}_5$  (refractive index of 2.15) films deposited on the lens. The surface reflections were then measured, and they ranged from 0.25 to 4 % for wavelengths between 1510 to 1610 nm.

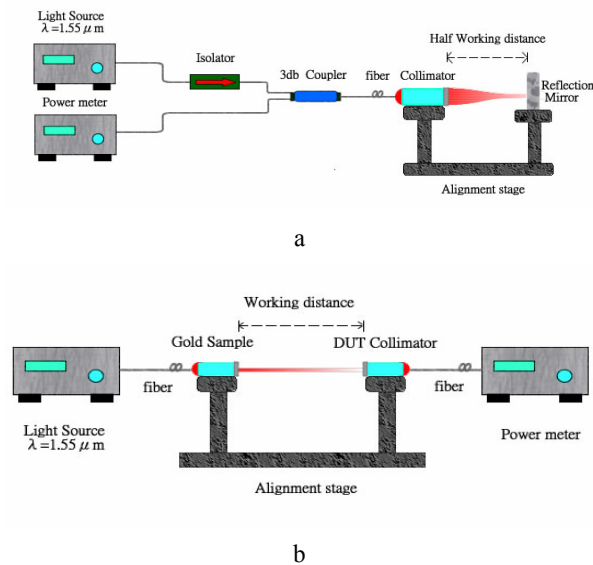


Fig. 3. (a) Setup for collimator gold sample fabrication  
(b) collimator measurement with gold sample.

In order to measure the insertion loss of each lens, the half working distance of each lens is first measured (Fig. 3a). The setup consists of a 1550 nm Fabry-Perot laser diode, an isolator (to prevent coupling of input and reflected light), a 3 dB  $2 \times 1$  fiber coupler, and an optical power meter (RM3, JDSU Inc., Milpitas, Canada). D lens and fiber pigtail were assembled with the assistance of a micro-stage. A mirror mounted on a separate micro stage is then moved to the half working distance position. The gap between fiber pigtail and D lens was then adjusted until the minimum reflection power is observed in the power meter. The lens is spliced with the light source and worked as an input collimator. The collimator under test (C.U.T) was then placed at a 20 mm working distance (W.D.) (Fig. 3b). The gap between the C.U.T. and its coupling fiber pigtail was adjusted until the lowest insertion loss is reached. The pigtailed fiber is then adhered to the glass tube by using UV cure epoxy exposed 10 minutes under a  $4000 \text{ mW/cm}^2$  365 nm wavelength UV lamp.

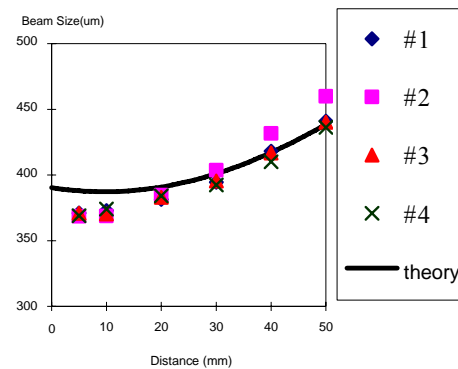


Fig. 4. Beam diameter versus output distance for four compact D lens collimators with same working distance

The power is received using a power meter spliced with a receiving collimator. The beam spot size of collimator at different far field position is measured using a beam scanner (model XYGET, Photon Inc., USA). A stable 0.4 mWatt 1550 nm wavelength Fabry-Perot laser diode was used as the light input. Assuming a Gaussian beam profile, the spot size exited from the collimator is defined as the diameter from the central maximum to the location where the power intensity decreases to  $1/e^2 \approx 13.5\%$  of beam center. Beam diameters as a function of the output distance,  $d$ , from 5 to 50 mm were measured for 4 D-lens collimators of 20 mm working distance (Fig. 4). The beam diameters were in the range of  $380 \sim 400 \mu\text{m}$  as the output distance varies from  $10 \sim 30 \text{ mm}$ . A Comparison of the theoretically calculated results and the experimental data, we find that when the

output distance is larger than 20 mm, the calculated results are in good agreement with the experiment data. However, the equation (3) becomes less accurate in approximating the beam diameter when the output distance is less than 20 mm. This is due to the fact that the errors will be raised from the limitation of the ray optics approximation in the near field region when the output distance becomes too short.

The optical loss measurement of two D-lens collimators with the same working distance was performed with a 1550 nm Fabry-Perot laser diode. Two collimators were mounted on a stage outfitted with a four-axis precise micro-stage to align the collimators. A power meter RM3 was used for optical power measurement. The optical loss between two GRIN-lens collimators was measured and compared with the D-lens. The compact-size D lens and GRIN lens are fabricated by Nippon Electron Glass Co., Ltd. and Nippon Sheet Glass Co., Ltd., respectively. Insertion losses of the different type collimators are calculated analytically by Eq. (4) and measured experimentally as a function of the output distance. Figure 4 demonstrates the theoretical and experimental results. It is seen that the lowest insertion losses for both types of collimators are almost the same at working distance of 20mm. However, GRIN lens shows slightly more sensitive to the output distance (Fig. 5). For GRIN lens, by varying the working distance 10 mm, insertion loss increased by 1.6 dB. As for the D lens, the insertion loss was reduced by 0.05 dB. This is due to the fact that the length of GRIN lens (2.6 mm) is shorter than the D lens (3.5 mm); therefore the beam diameter of GRIN lens varied more significantly. As a result, the GRIN lens's beam divergence angle is larger than D lens's and insertion loss is more sensitive to the output distance.

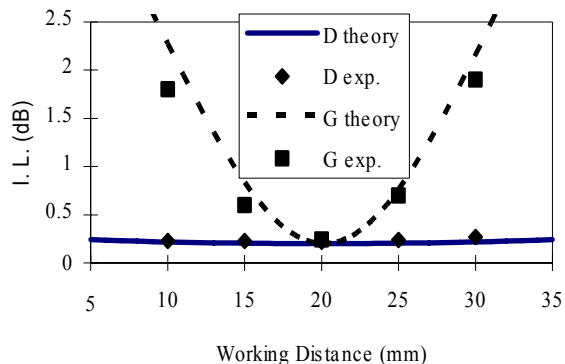


Fig. 5. Plot of insertion loss versus working distance. The figure shows compact-size D lens collimator is insensitive to a small change in the working distance. Here symbols D and G represent D lens and GRIN lens collimators.

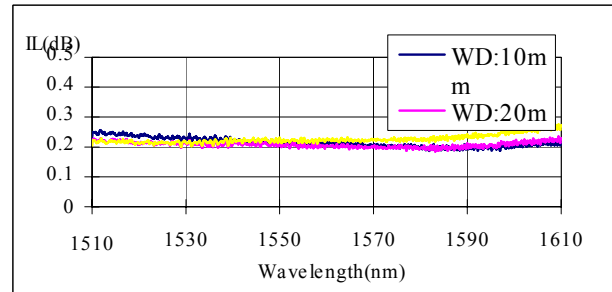


Fig. 6. Insertion loss spectrum of D-lens collimator for output distance 10mm, 20mm, and 30mm.

In theoretical analysis, all the reflection loss, the material absorption loss and the misalignment loss were not considered, but in reality they contributed about 0.2 dB insertion loss. This loss includes a 0.06 dB from the AR coating and a 0.14 dB from the misalignment. Therefore, 0.2dB added to the insertion loss to insure same conditions is applied to the theoretical calculation. For the D-lens collimators, the experimental data agree well with theoretical results. However, the results do not match well for the GRIN-lens. The reason is that the D-lens is made of a homogeneous material. Thus the typical ball lens model works. For GRIN lens, owing to the graded index distribution, it is hard to use a very precision model to accurately predict all the parameters (i.e. index profile). Therefore this leads to some discrepancy between experimental and theoretical results. We further test the insertion loss of the D lenses in the range of 1510 ~1610 nm measured at the output distance of 10 mm, 20 mm, and 30mm using an amplified spontaneous emission (ASE; BBN Co. Ltd., Taipei, Taiwan) light source and an optical spectrum analyzer (6315E, Ando Inc., Tokyo, Japan). The experimental result shows that the insertion losses are less than 0.3 dB (Fig. 6), in agreement with our theoretical calculation.

#### 4. Conclusions

A compact-size D lens collimator has been fabricated and the beam size and insertion loss were measured and analyzed. The theoretical analysis was also conducted based on ABCD matrix method and Gaussian beam theory. Based on the theoretical results, for designing a 20 mm working distance collimator, the optimum gap, 260  $\mu\text{m}$ , was obtained and beam waist radius was measured at around 193  $\mu\text{m}$  at  $d = 10$  mm, which was experimentally verified. For the D-lens, an insertion loss of less than 0.3 dB in an output distance ranging from 10 mm to 30 mm was observed. With these newly discovered features along

with lower cost material and simple fabrication procedure, it makes the D-lens be a better choice for fiber collimator that is currently used in the fiber communication and micro-optics devices.

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### References

- [1] J. J. Pan, Y. Yu, J. C. Jiang, J. Guo, K. Guan, Y. Zheng, Novel passive free space compact CWDM Technology for outdoor applications, OFC 2006, March 5-10, Anaheim, California, USA.
- [2] T. Gamano, T. Hattori, K. Motojima S. Hirai, Compact 1.31 & 1.49/1.55  $\mu\text{m}$  WDM using fiber type lens, OFC 2006, March 5-10, Anaheim, California, USA.
- [3] Q. Jianxin, H. Feng, Study on angle deviation for coupling loss in fiber collimator packaging, Electronic Packaging Technology, 2005 6<sup>th</sup> international conference on 30-02 Aug. 2005
- [4] H. Y. Park, S. W. Ha, M. J. Kim, S. G. Lee, S. G. Park, B. H. O, E. H. Lee, Ray model of an incident Gaussian beam for analyzing a micro-optical communication device with a GRIN lens system, Opt. Rev. **12**, 233 (2005).
- [5] Loe Shiefman, Insertion loss comparison of microcollimators used to propagate light in and out of single-mode fibers, Opt. Eng **43**, 1927 (2004)
- [6] W. L. Emkey, C. A. Jack, Analysis and Evaluation of Graded-Index Fiber-Lenses, J of Lightwave Technol., LT-5, 1156 (1987).
- [7] F. A. Rahman, K. T. akahashi, C. H. Teik, A scheme to improve the coupling efficiency and working distance between laser diode and single mode fiber, Opt. Communi. **208**, 103 (2002).
- [8] W. Bludau, R. H. Rossberg, Low-loss laser-t-fiber coupling with negligible optical feedback, J of Lightwave Technol. LT-3, 294 (1985).
- [9] Amnon Yariv, Optical Electronics in Modern Communications, 1997
- [10] M. V. Buren, N. A. Riza, Foundations for low-loss fiber gradient-index lens pair coupling with the self-imaging mechanism, Appl. Opt. **42**, 550 (2003).

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