# Achievement of Large Spot Size and Long Collimation Length Using UV Curable Self-Assembled Polymer Lens on a Beam Expanding Core-Less Silica Fiber

J. Kim, M. Han, S. Chang, Jhang W. Lee, and K. Oh

*Abstract*—**We report a novel three-segmented fiber-collimator using self-assembled fluorinated polymer lens and a beam expanding coreless silica fiber of 200-$\mu$m diameter spliced to single-mode optical fiber. Both numerical and experimental analyses are presented for design, fabrication, and optical characterization of the device. We have obtained a working distance over 6 mm and a stable spot size over 50 $\mu$m in a wide wavelength range of 1.51–1.59 $\mu$m.**

*Index Terms*—**Collimation, coreless silica fiber (CSF), large spot size, lensed fiber, polymer lens.**

## I. Introduction

MASSIVE implementation of optical networks will inevitably generate rapidly growing demand for optically and mechanically stable interconnection based on optical fibers [1]. Free-space interconnection devices, such as in-line isolator, in-line filter, fiber pigtailed transceivers, and arrayed waveguide grating, are growing in their market demands and all of them require flexible design in working distances and spot sizes for efficient optical coupling. In order to cope with these trends, various types of lensed fibers are being developed such as a wedge fiber, graded index lensed fiber, and photolithographic lensed fiber using polishing, arc-discharging, and photolithography method [2]–[4]. Moreover, with the advent of optical microelectromechanical systems devices, collimation of fiber output and input in the form of Gaussian beam has been at the center of interests for small form factor packaging without degrading optical performances. Single-mode fiber (SMF) compatible collimator with a long working distance and stable spot size, would be main characteristics required in SMF optical interconnections [5]. A novel three segmented structure ultraviolet (UV)-curable liquid polymer lens, coreless silica fiber (CSF) on conventional SMF, has been recently proposed by the authors [6]–[8]. The technique is based on flexible control of radius of curvature of UV curable polymer lens along with beam expansion in the CSF segment to achieve good tolerance and tight focusing.

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In this letter, we report a new degree of freedom, the diameter of the CSF in the three-segmented structure, can play a decisive role to manipulate the optical coupling characteristics. We experimentally demonstrated a compact three-segmented fiber collimator with a long working distance and wide wavelength range of operation, for the first time to the best knowledge of the authors.

## II. Device Fabrication and Theory

The fabrication process for the proposed three-segmented fiber lens has been previously reported elsewhere[7], [8]. In the three-segmented fiber lens, the $LP_{01}$ mode out of SMF will propagate through CSF and its mode field will expand. The polymer lens at the exit will collimate or focus the beam with an appropriate radius of curvature. Note that the physical dimensions of CSF, its diameter and length, will determine the degree of beam expansion and accordingly the requirements for polymer lens performances.

To analyze the fiber lens system, we approximated the modal distribution at the input-fiber end by a Gaussian profile, and the ray matrix transformation of the complex beam parameter after Kogelnik [9] is utilized. Ray matrices in the proposed devices are listed in Fig. 1, for the input and output planes at the interfaces of the fiber segments and free space. The effective ABCD elements are obtained from

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = M_{34}M_{23}M_{12} \tag{1}$$

where $M_{ij}$ is the matrix describing the transformation of the ray parameters between interface $i$ and $j$. We find

$$A = 1 + \frac{n_0 - n_s}{n_0 R}Z, \quad B = \frac{n_s}{n_0}Z + L_s\left[1 + \frac{n_0 - n_s}{n_0 R}Z\right],$$
$$C = \frac{n_0 - n_s}{n_0 R}, \quad D = \frac{n_s}{n_0} + L_s\frac{n_0 - n_s}{n_0 R}. \tag{2}$$

The working distance $Z$ and spot size $w_f$ can be obtained with (3) and (4), respectively [9]

$$AC + a^2 BD = 0 \tag{3}$$

$$w_f = w_i\left\{\frac{n_s}{n_0}\frac{A^2 + a^2B^2}{AD - BC}\right\}^{1/2}, \qquad a \equiv \frac{\lambda}{\pi w_i^2 n_s}. \tag{4}$$

Beam propagation after SMF can be controlled in the CSF segment by changing its diameter and length. Fig. 2 shows two

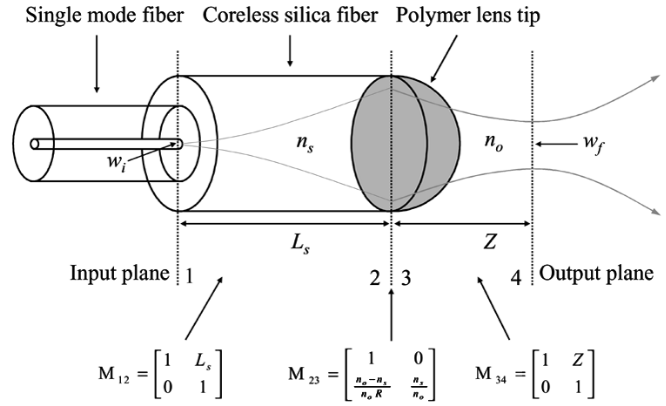



Fig. 1. Schematic view of the proposed fiber lens and ABCD Law for beam propagation calculation: $n_s$ and $n_o$ are the refractive indexes of the CSF and air, respectively; $w_i$ and $w_f$ are the initial and final spot size, respectively; $L_s$ is the length of CSF; $Z$ is the distance from the fiber end to the beam waist; working distance is double of $Z$.

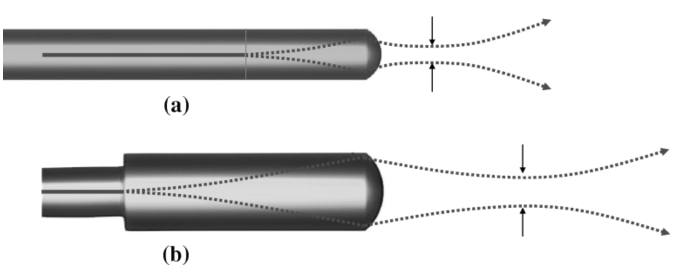



Fig. 2. Beam propagation along three segmented fiber lesnses with CSF of diameter of (a) 125, (b) 200 $\mu$m.

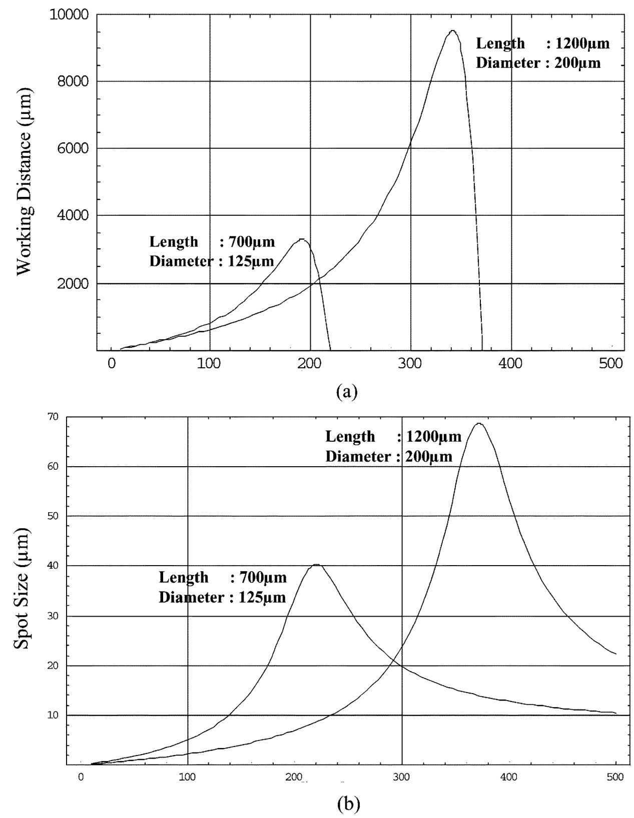
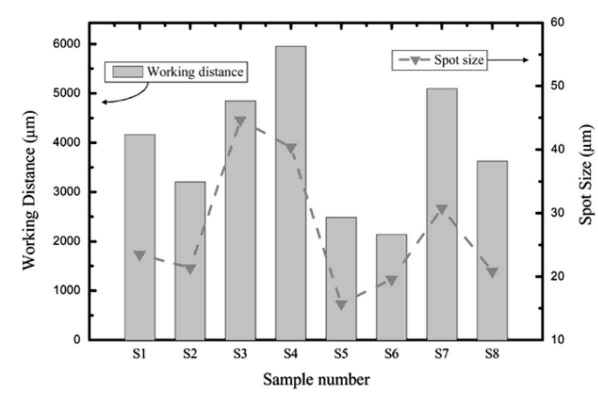



Fig. 3. Maximum working distance and spot size as a function of radius of curvature. (a) Working distance versus radius of curvature. (b) Spot size versus radius curvature.

types of lensed fibers for the 125- and 200-$\mu$m CSF diameters. In Fig. 2(b), we expect expansion of the mode field by the larger CSF diameter, which subsequently enables a larger radius of curvature in the polymer lens to form a collimator [6]. Monotonic increment in the CSF length, however, is not always optimal for beam expansion. Concentric interference fringes occur after a certain length of CSF, which is attributed to reflection of light at the CSF-air boundary. CSF length, therefore, should be optimized considering the tradeoff between beam-expansion and multiple path interference. The optimal length of 125-$\mu$m CSF is calculated around 700 $\mu$m while that of 200-$\mu$m diameter CSF is 1200 $\mu$m using a commercial beam propagation method package. For these two types of CSFs, we calculated the maximum working distance and spot size for various curvature radii of polymer lenses and the results are shown in Fig. 3. It was found that 200-$\mu$m diameter CSF excel 125-$\mu$m CSF in both working distance and spot size. A 200-$\mu$m diameter CSF will provide a working distance four times longer and a spot sized two times larger than 125 $\mu$m counterparts.




| Sample number | #1 | #2 | #3 | #4 | #5 | #6 | #7 | #8 |
|---|---|---|---|---|---|---|---|---|
| R (μm) | 251 | 259 | 294 | 318 | 272 | 318 | 321 | 322 |
| Lc(μm) | 1000 | 1000 | 1100 | 1100 | 1150 | 1200 | 1200 | 1200 |

Fig. 4. Experimental measurements of working distance and spot size for different samples.

## III. Experiments and Results

CSF segments of 200-$\mu$m diameter were prepared with the length range of 1000–1200 $\mu$m. We have fabricated lens using a fluorinated acrylate polymer that mainly consists of fluorinated oligomer and monomers with 1 : 1 ratio along with the acrylate monomer of 3%–5% and a small dose of photoinitiator of 2%–4% for UV-curing [8]. The polymer was provided by Luvantix and it was synthesized based on one of its products, EFIRON-WR346. After making identical fiber lens pairs, the working distances and spot sizes were measured at 1550 nm as in Fig. 4. By optimizing the CSF length and the radius of curvature in the polymer lens, we could obtain a long working distance over 6 mm, and a spot size over 50 $\mu$m, which makes

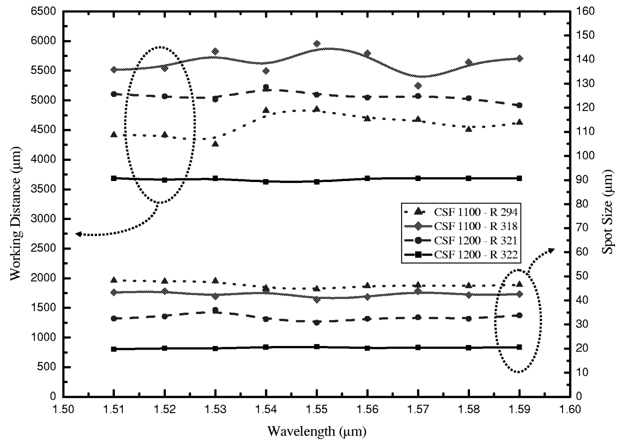



Fig. 5. Spectral response of working distance and spot size.

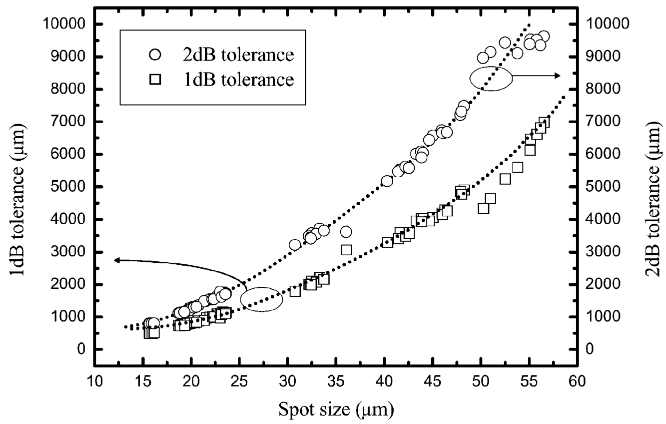



Fig. 6. 1-dB tolerance and 2-dB tolerance length as a function of spot size for axial displacement.

the device a potential replacement for bulk GRIN rods. Fig. 5 shows the variation in the working distance and spot size over the spectral range 1510–1590 nm. Variations less than 3% in the working distance and less than 8% in the spot size were obtained in the 80-nm bandwidth. This means that the proposed device has a strong potential to provide a uniform spectral response in the entire $C$-band and parts of $S$-band, $L$-band with a further optimization. Composite chromatic dispersion of silica and UV curable polymer was attributed for this broad-band of operation.

For longitudinal displacement, the device showed superb performances in the power penalty tolerance, as shown in Fig. 6. For the spot size of 55 $\mu$m, 1- and 2-dB penalty lengths were about 6 and 9 mm, respectively, and they were directly proportional to the square of the spot size [10]. The minimum loss at the optimal displacement was measured to be 1.5 dB, which is of the same magnitude as prior reports. The impact of lateral displacement was also measured at 1.55 um and summarized in Fig. 7. A 1-dB tolerance range of $\pm 18$ $\mu$m for the lateral displacement, shown in open circles, was significantly narrower compared with the longitudinal displacement. However, it was an order of magnitude larger compared with direct SMF coupling, shown in open triangles.

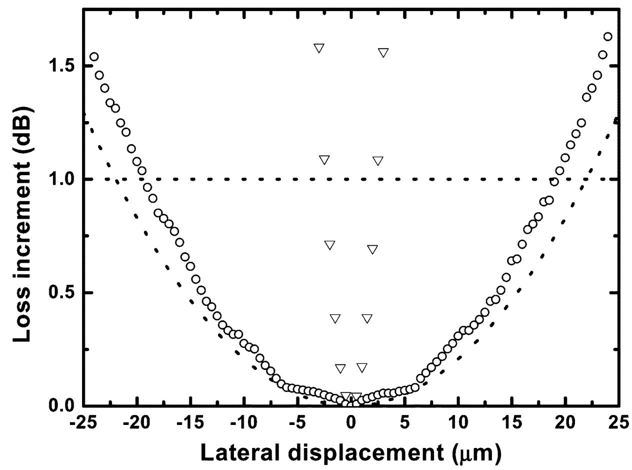



Fig. 7. Optical loss increment as a function of lateral displacement. The dotted line is theoretical prediction and the open circles are measurement for the fiber lens. The open triangle is for SMF-SMF coupling.

## IV. Conclusion

A CSF segment with a larger diameter of 200 $\mu$m have been adapted in a three-segmented fiber lens in order to provide a longer working distance and a larger spot size for fiber-collimator applications. Analytic formulae for optimization of CSF diameter and length have been obtained for optimal collimation. We manufactured the fiber collimator whose working distance over 6 mm with less than 3% variation and spot size over 50 $\mu$m with less than 8% variation in the wide spectral ranges, 1510–1590 nm. We confirmed that the devices have an ample potential optical interconnection for both DWDM network and access network devices.

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