Optimized design of trenched optical fiber for ultralow bending loss at 5 mm of bending diameter

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We propose a bend-insensitive optical fiber with optimized design for the ultralow bending loss at 1550 nm for 5 mm of bending diameter, with a wide cutoff wavelength tolerance.

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1. Introduction

With the rise in the use of fiber-to-the-home (FTTH) applications in optical fiber communication systems, various research groups and companies are developing products to meet the stringent requirements of FTTH applications [1–5]. In FTTH-type optical communication systems, the conventional single-mode fibers (SMF, G.652.D) that use the uplink and the downlink with 1.31 and 1.55 μm wavelength, respectively, are replaced by bend-insensitive optical fibers (BIF) having very low bending loss. Modern-day BIFs that follow the ITU-T standard [6] have been standardized under the G657 Class B standard, which has very stringent bend loss requirements, for example, maximum bending loss <0.5 dB/loop at 1550 nm at 15 mm (φ15) of bending diameter. There are several reported optical fibers that meet and exceed the bending loss requirement of G657.B, thereby providing the bend optimized performance [3,4]. To name a few, the G657.B/G652.D compatible optical fiber having nanoengineered holes around the core has been reported to have a bending loss of 0.03 dB/loop at 1550 nm at 10 mm of bending diameter [4], and similar fiber with a low index trench around the core has shown bending loss of about 0.05 dB/loop [3]. Our research group has also reported the lowest bending loss for the BIF by utilizing the management of trenches around the core [7–10]. Measurement of the cutoff wavelength of BIFs has been also reported in [11].

However, actual commercialization of these BIFs has faced major hurdles: (i) when the φ10 optimized BIF is used at the sharp bending loop of 5 mm diameter (φ5), the bending loss increases at least by ten times as compared to that of φ10 BIF. For example, the bending loss of several BIFs (φ10 optimized, developed by our group) having negligible bending loss was found to be between 1.5 dB/loop to 27 dB/loop at φ5 (1550 nm). (ii) Shift of the LP_{11} cutoff wavelength to higher value than the original. We found that this change of the cutoff wavelength of BIFs occurs for small modifications in trench radial parameters.

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Table 1. Comparison of FiberCAD Simulation Results and Measured Bending Losses for Various Bend Insensitive Optical Fibers[a]

	$b(\mu\text{m})$	$c(\mu\text{m})$	Δn_{Trench}	Bending Loss (FiberCAD) dB/loop	Bending Loss (Experimental) dB/loop
Fiber-1	2.35	11.3	−0.0048	0.002	0.026
Fiber-2	4.13	13.53	−0.0045	0.0034	0.044

[a]The loop diameter was 10 mm, and the bending loss was measured at 1550 nm.

Considering problems faced during fabrication of a BIF, the very first need is to allow a wide flexibility in choosing parameters of the optical fiber, so that experimental realization is fruitful. Second, another set of optimized parameters of a BIF is needed if we are looking for the bend insensitivity at the sharp bend of 5 mm diameter. With this motivation, in the current communication, we report optimized parameters of a BIF with a wide cutoff wavelength tolerance and an ultralow bending loss (<0.05 dB/loop) for 5 mm of loop diameter at 1550 nm.

2. Simulation

The macrobending loss, in the units of decibels/kilometer, was calculated using [12–14]:

$$\alpha_{\text{macro}} = \frac{10}{\text{Log}_e 10}\left(\frac{\pi V^8}{16 r_c r_b W^3}\right)^{1/2} \times \exp\left(\frac{-4 r_b \Delta W^3}{3 r_c V^2}\right)\frac{\left[\int_0^\infty (1-g) F_0 r \mathrm{d}r\right]^2}{\int_0^\infty F_0^2 r \mathrm{d}r}, \quad (1)$$

where F_0 is the radial field of fundamental mode, r_c denotes the fiber core radius, r_b is the bend radius, $n_{\max}$ and $n_{\min}$ are the maximum and minimum values of refractive index and other parameters appearing in the above equation are given by

$$g = \frac{n(r)^2 - n_{\min}^2}{n_{\max}^2 - n_{\min}^2}, \qquad V = k_0 r_c \sqrt{n_{\max}^2 - n_{\min}^2},$$
$$\Delta = \frac{n_{\max}^2 - n_{\min}^2}{2 n_{\max}^2}, \qquad W = r_c \sqrt{\beta^2 - (k_0 n_{\min})^2}. \quad (2)$$

We used the commercial FiberCAD code to solve the propagation equations and to calculate the bending loss of optical fiber [12]. With regard to the validity of using Eq. (1) and the FiberCAD code to determine the bending loss, it is worth mentioning that the use of the FiberCAD code for designing the optical fiber has been quite often carried out by researchers [7–11,15–17]. In our experimental investigations on the BIFs, we found that the bending loss results obtained by the FiberCAD code match qualitatively to the measured data. A short comparison of the FiberCAD results and measured bending loss data has been given in Table 1. Measured bending losses were found to be approximately 10–13 times higher than theoretically predicted bending losses by the FiberCAD code and this factor was considered in designing a $\varphi 5$ optimized BIF as mentioned in the following discussion.

For the bend insensitivity in optical fibers, we chose the trenched optical fiber, because it is being already optimized for $\varphi 10$ operation, and we can readily use these results for $\varphi 5$ optimized BIF. Other optical fiber parameters of the BIF were chosen to be similar to the commercial SMF: (i) the mode-field diameter at $1310 = 8.3\,\mu$m to $9.1\,\mu$m, (ii) cutoff wavelength $< = 1260$ nm, except for the bending loss, theoretical bending loss of the BIF was chosen to be $< = 0.0037$ dB/loop for $\varphi 5$ at 1550 nm. It is noted that as per our earlier experimental studies regarding the BIF, the theoretical bending loss of 0.0037 dB/loop calculated by [12–14] for 5 mm of bending diameter (at 1550 nm) corresponded to the experimental bending loss of approximately 0.05 dB/loop. For the core part of the BIF, the core diameter of $8.2\,\mu$m and the core-cladding index difference of 0.005 were chosen, which were typical step index SMF parameters. The BIF under consideration is shown in Fig. 1.

As we mentioned earlier, the cutoff wavelength of the BIF is very sensitive to its trench parameters. To have a direct insight into the variation of the cutoff wavelength, we simulated a nonoptimized BIF profile; the fiber parameters were: $\Delta n = 0.005$, $a = 4.1\,\mu$m, $b = 8.2\,\mu$m, $c = 4.1\,\mu$m, and $\Delta n_{\text{Trench}} = -0.007$, unless the parameter is varied. As shown in Fig. 2, the cutoff wavelength showed increment with increase in c/a, while it decreased with increasing Δn_{Trench}. Thus, these two parameters (c/a and Δn_{Trench}) can be used to counter the shift in the cutoff wavelength. Additionally, an effect of trench separation from the core of optical fiber on the cutoff wavelength is shown in Fig. 3, where it can be observed

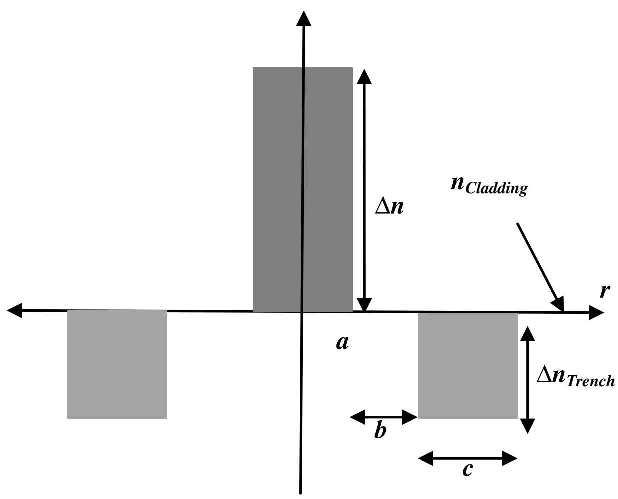

Fig. 1. Bend-insensitive optical fiber (BIF).

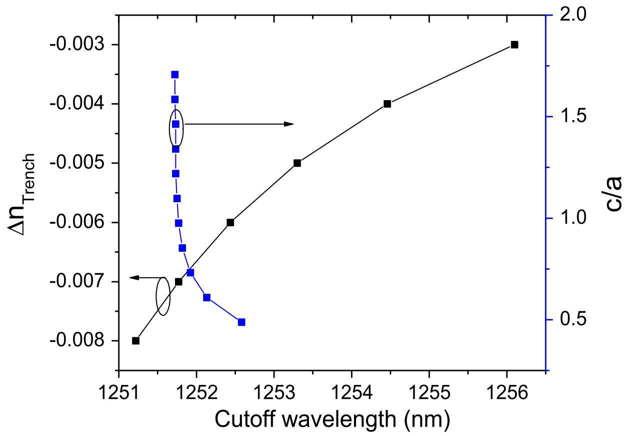

Fig. 2. (Color online) Effects of trench index difference and trench width on the cutoff wavelength.

that the cutoff wavelength is very sensitive to the separation of trench from the core. However, selecting b equal to some incremental value $b_{\max}$ can ensure the single-mode operation at desired wavelength; our task is then to determine this maximum value of b, i.e., $b_{\max}$.

As per G652 recommendations, for the optical fiber with 22 m length, the cable cutoff wavelength should be less than 1260 nm and for the fiber length less than 2 m, it should not exceed 1250 nm [6]. In a view to justify the compliance of the theoretical cutoff wavelength calculated in the current manuscript with that of the one mentioned in ITU-T recommendations, we measured the cutoff wavelength of various fibers (22 m) and compared them with LP_{11} mode cutoff values determined by FiberCAD, which are listed in Table 2. In Table 2, the in-laboratory developed BIF (Fiber-3) was a double-trenched fiber and it had the following parameters: inner and outer trench indices were –0.005 and –0.0046, respectively, inner and outer trench widths were 7.1 and 5.7 μm, respectively, inner trench was separated from the core by 6.75 μm, separation between two trenches

Table 2. Comparison of Theoretical Cutoff Wavelength with the Experimental Results for Three Different Fibers

	Fiber-1 (SMF) [19]	Fiber-2 (BIF-1) [1]	Fiber-3 (BIF-2)
Theoretical value	1332.05 nm	1373.1 nm	1360.8 nm
Bending loss method (22 m fiber)	~1231.3 nm	~1265.6 nm	~1256.3 nm

was 4.6 μm, and the core radius was 4.45 μm. It can be observed in Table 2 that the theoretical cutoff wavelength is far more than the measured cutoff wavelength and it can be stated that with the theoretical cutoff values that we have selected in the manuscript ($<=$ 1260 nm), it will always insure that the experimental cutoff wavelength is always less than 1260 nm as per ITU-T recommendations.

3. Results and Discussion

By choosing core parameters as explained in an earlier section, we simulated the BIF profile for various values of trench depth. It was found that to obtain the bending loss $<= 0.0037$ dB/loop for $\varphi 5$ at 1550 nm, the trench index depth must be less than about –0.0072; other parameters do not cause significant modification in the bending loss value. Therefore, initially, Δn_{Trench} was fixed at –0.0072. As shown in Fig. 2, the cutoff wavelength showed rapid change with c/a approaching 0.5; considering the possible worst case scenario of fabrication of the BIF where the value of c is 50% of the core radius, c/a was also initially fixed at 0.5. Using these parameters, we changed b/a, which gave the optimized $b/a >= 0.8$. By imposing the dispersion and mode-field diameter condition, the range of b/a was taken to be 0.8–1, as shown in Fig. 4.

Finally, rigorous calculations were carried out for various trench parameters and the set of optimized parameters that satisfy the design criteria were obtained, which are shown in Fig. 5 where variations in c/a, Δn_{Trench} are shown at various b/a values. It is noted that while fabricating the BIF, its Δn_{Trench}

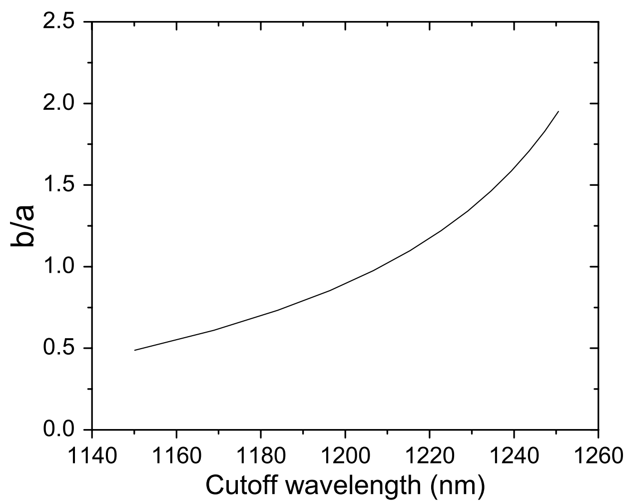

Fig. 3. Effects of trench separation on the cutoff wavelength.

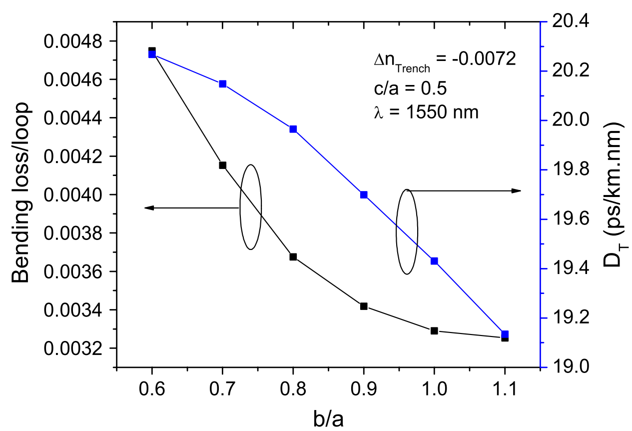

Fig. 4. (Color online) Effects of trench separation on the bending loss and dispersion characteristics. Bending loss was determined at the loop diameter of 5 mm.

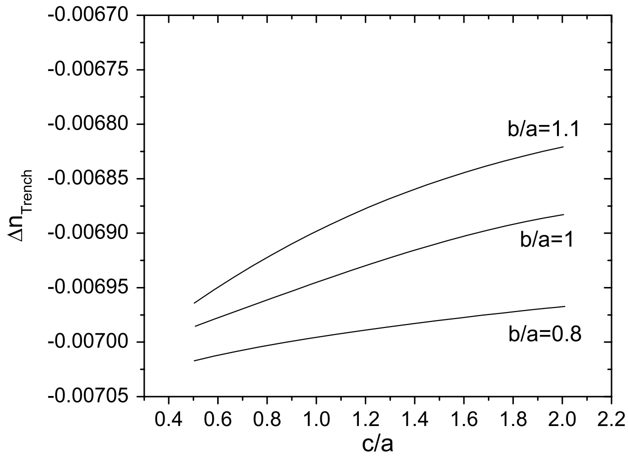

Fig. 5. Optimized trench parameters of the BIF.

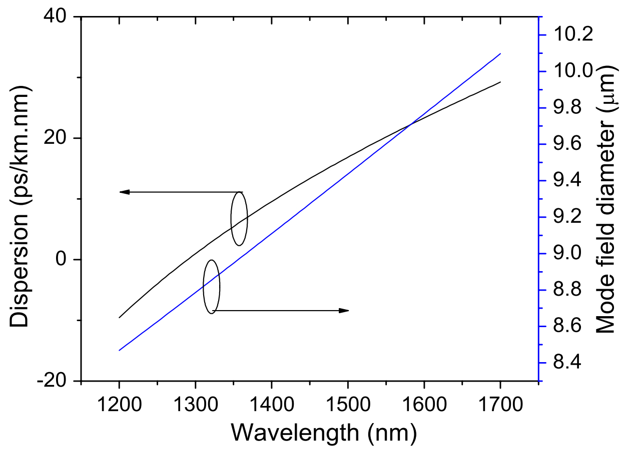

Fig. 7. (Color online) Spectral variations of the dispersion and the mode-field diameter of optimized BIF.

value should be less than the mentioned Δn_{Trench} value in the curve so that the imposed conditions of the bending loss, cutoff wavelength, and dispersion are followed. Using these results, the optimized BIF parameters can be extracted as per need. For instance, at $c/a = 0.5$ and $b/a = 1.1$, choosing the value of $\Delta n_{\text{Trench}} <= -0.00696$ will always give the bending loss $< = 0.0037$ dB for a loop of 5 mm diameter at 1550 nm.

Actual variation of the bending loss, the mode-field diameter, and the dispersion is shown in Figs. 6 and 7 for the typical parameters (chosen from the optimized range): $\Delta n_{\text{Trench}} = -0.008$, $c/a = 1$, and $b/a = 1$. It can be observed that the bending loss is 0.001/loop dB for $\varphi 5$ at 1550 nm for the fiber parameters mentioned. Also, the cutoff wavelength for this BIF design turns out to be 1206 nm, thus fulfilling all goals for the BIF optical properties as mentioned earlier. When simulated for the optimized parameters of the BIF, its zero dispersion wavelength showed wide dependency on trench parameters, as shown in Fig. 8. It was observed that increase in the depth of trench or increase in its width caused the zero dispersion wavelength to decrease, while increase in the separation of trench from the core caused the zero dispersion wavelength to increase, as shown in Fig. 8. It is noted that the zero dispersion wavelength dependency on the trench depth was much higher than the width and separation parameters.

Before concluding, it is worth commenting on the mechanical viability of BIFs in FTTH for sharp bends of 5 mm diameter; a rough estimation about it can be drawn from the critical bending radius: $R_c = \frac{3n_{\text{Clad}}\lambda}{4\pi(\text{NA})^3}$, where NA is the numerical aperture, n_{Clad} is the cladding index, and λ is the wavelength. For the NA of 13.18%, the critical bending radius turns out to be about 0.24 mm, which is far less than the 5 mm bending diameter that has been targeted in the current manuscript. During our various experiments with regard to BIF, the in-laboratory uncabled optical fiber showed a breaking problem during 5 mm diameter windings; average breaking occasions were five in 100 samples. The existence of boron in the trenched layer could have contributed to the poor strength of the BIF. However, for the commercial

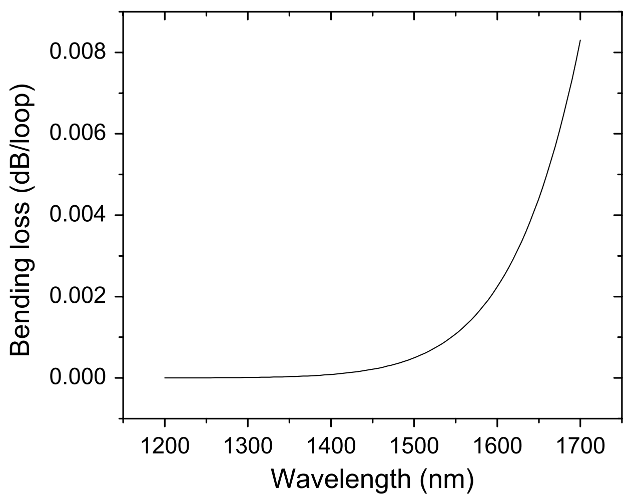

Fig. 6. Spectral variation of the bending loss of optimized BIF.

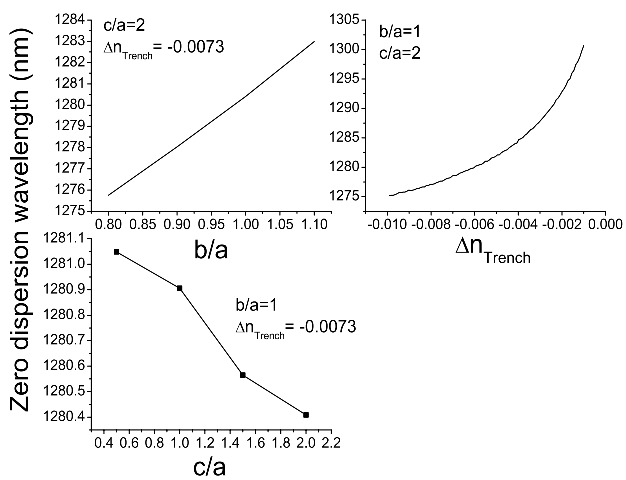

Fig. 8. Dependence of zero dispersion wavelength on trench parameters.

BIF, reliability should not be a issue for 5 mm of bending diameter. As pointed out in [18], the reliability of an SMF with 5 mm of bending diameter can be extrapolated to be 30 per 1000 samples [18], while we observed it to be about 50 per 1000 samples for the in-laboratory made BIF.

4. Conclusion

We proposed optimized parameters for the design of a BIF so that it follows the optical properties of the commercial single-mode optical fiber with the bending loss of less than 0.05 dB/loop for $\varphi 5$ at 1550 nm.

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