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# Highly bend compensated large mode area segmented cladding fiber with high index circular multitrench in core

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**Abstract**
A bend resistant segmented cladding fiber with high index circular multi trench in the core region is designed to attain single mode condition and large mode area (LMA). Pure silica based low refractive index trenches are introduced around the core region for reducing fabrication complexity. The high index circular multi trench is supported to avoid the mode area distortion at tight bending radius of 7.5 cm. The lasing parameters such as bending loss and mode area of the proposed fiber is investigated by varying structural parameters at the lasing wavelength of 1.06 µm. The numerical outcomes demonstrate that the proposed LMA fibre is able to operate in single mode (SM) condition with an effective mode area of 1006 $\mu m^2$. Additionally, the obtained loss ratio between the basic mode ($LP_{01}$) and the lowest higher order mode ($LP_{11\text{-odd}}$) is 162, which confirms effective single mode operation. The proposed fibre will be crucial in the development of high power fibre laser, fibre amplifier, and high power delivery applications.

**Keywords** Large mode area fiber · Segmented cladding fiber · SM operation · Multi trench · Fundamental mode and higher order mode

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## 1 Introduction

Recently, the development of high power fibre lasers has been so rapid that the maximum output power of a single mode continuous wave laser has reached 10 kW with diffraction-limited beam quality (Nilsson 2011). It have numerous advantages compare with solid state lasers and semiconductor lasers such as thermal management, easy manufacturing, high reliability, robust, scalable output power, and high beam quality. However, a number of issues, such as mode instability, substantial thermal damage and nonlinear effects, have an impact on the beam quality and output power for increasing power level. The fibre nonlinear effect turns out to be the most significant difficulty as laser output power increases (Agrawal 2000). Large mode area (LMA) fibres have drawn a lot of interest because of its potential to address high power's problems which reduce the nonlinear effects. Further, to maximize the effective mode-area for lasing application, single-mode condition must be used to obtain effective beam quality. The potential applications of LMA fiber lasers are optical communication, industrial, medical and spectroscopy (Jeong et al. 2004; Richardson 2010; Limpert et al. 2002). Numerous LMA fibre lasers have recently been produced and put through numerical analysis. It can be obtained by enlarging the core, but several modes propagate in the fibre and also reduce the numerical aperture (NA) which very difficult to maintain SM operation. LMA fibre bends in order to get compact fibre in practical situation, which reduces mode area and beam quality. In 2015, LMA fibre with minimum NA was proposed by Jain et al. and manufactured by the modified chemical vapour deposition method (MCVD) with core diameter 35 µm. The bending characteristics were examined using a 16 cm bending radius to obtain a modal area of 700 µm$^2$ (Jain et al. 2015). Further, photonic crystal fibre also (PCF) is supported to maximum LMA with SM operation for alternative to conventional step index fibres. For instance, negligible bending loss has been found for PCF with huge core diameters of 100 µm (Brooks and Di Teodoro 2006). But at practical bending radius of 5–10 cm, mode-area declines, which is the constraint for LMA PCF designs (Wang et al. 2013). A substitute for PCF that prevents mode-area shrinking is leakage channel fibre (LCF). LCFs are made of one or a few low-index rods in cladding. By optimizing the pitch and diameter of low index rods in LCF, which provide flexibility in managing the confinement loss for fundamental mode and higher order modes for attaining endlessly single mode operation. Initially, LCF developed with 100 µm core diameter by Linag dong and obtained mode area of $>1000$ µm$^2$at 6.7 cm bending radius (Dong et al. 2007). However, the big air holes cause a variety of practical issues such as air holes collapsed and heat dissipation. To overcome above mentioned issues, LCFs were changed to have an all-glass structure with fluorine-doped rods in place of the air holes. Nevertheless, it is challenging to bend the all-glass with fluorine-doped rods LCF into a tight bending radius and also weak confinement capability than air holes. In 2014, LCF with microstructure cladding air holes designed for obtaining fundamental mode mode area of 1400 µm$^2$and bend loss of $<3$ dB/turn at the bending radius of 20 cm (Saitoh et al. 2011). However, due to a rather high device size, the intended bend radius of 20 cm is not optimal for compact laser systems.

Additionally, single and multi-trench fibres (MTF) are becoming more popular for obtaining SM condition and LMA at the 15–20 cm bending radii which can be fabricated by MCVD technique (Jain et al. 2014). Trench-assisted designs have the issue of satisfying endlessly single mode operation by effectively suppressing higher order modes. The main strategy to solve this problem is resonant coupling. It means higher order modes linked into resonate ring or cladding mode at particular thickness of resonant ring. So, higher order modes loss is high for tight bending condition (Jain et al. 2014; Jain et al. 2013). The bending orientation influences the coupling of higher order modes into the cladding ring to some extent. In 2016, multi trench (MT) in core LMA fiber designed and bending performances analyzed at 15 cm bending radius (Wang et al. 2015). At a relaxed bending condition of 20 cm, the mode-area of the gap-MTF is limited to 920 μm$^2$, and the reported differential bending loss ratio is 100 (Sun et al. 2015). These designs are not appropriate for the 7.5 cm practical packaging radius. For such fibre designs, the effective mode-area drastically decreases and difficult to maintain SM condition at the compact bending condition. In 2019, asymmetric clad MTF with high index arc proposed and attained mode area of 1300 μm$^2$at the compact bending radii of 7.5 cm (Kurade et al. 2019). But, it is very difficult to fabricate high index arc in the trench region. In addition, chirally coupled core (CCC) fibres (Towe 2017), gain-guided and index anti-guided (GG+IAG) optical fibres (Hageman 2010), segmented cladding fibres (SCF) (Millo et al. 2007), and multilayer cladding fibres (Kumar and Rastogi 2007)are used to accomplish LMA with single-mode operation. SCFs stand out among these well-designed fibres due to their SM operation over a wide range of wavelengths and their special skills of LMA and higher order modes suppression at the compact bending radius. SCF is made up of an extensive high index core and alternative arrangement of low and high index in cladding. It is supported to attenuate higher order modes with large mode field region at short range of length. Further, it is overcome the problems of conventional LMA fiber with better beam quality (Rastogi and Chiang 2004). In 2020, Guanli Wang et al., proposed pixelated trench assistant SCF for obtaining mode area of 914 μm$^2$ at relaxed bending radius of 20 cm (Wang et al. 2020). Further, resonant ring assisted LMA SCF designed with high index ring in the core region and obtained mode area of 835 μm$^2$ at lasing wavelength of 1.06 μm (Guo et al. 2021).

In this paper, we have proposed numerical analysis of SCF with four layer of high index circular multi trench in the core by finite element method. According to duty cycle, bending orientation angle, high index circular multi-trenches, low index trenches, the suggested fiber's bending loss and mode area performance are examined. At compact bending radius of 7.5 cm, minimum bending loss of 0.051 dB/m and mode area of 1006 μm$^2$ for mode is attained with lasing wavelength of 1.06 μm. The paper is organized as follows; Sects. 2, 3 and 4 described proposed model design and characteristics, properties of proposed LMA fiber and analysis of numerical bending characteristics by varying structural parameters (bending loss, mode area and loss ratio).

## 2 Design and modal characteristics

The cross sectional view of LMA fiber with high index circular multi trench segmented cladding fiber (MTSCF) and refractive index profile is shown in Fig. 1a and b, respectively. The proposed fiber is contained three regions. The dark brown regions indicates the pure silica layer whose refractive index ($n_L$) is $n=1.45$. The outer region radius is $R_d$ = 200 μm, which includes 45 μm of segmented cladding region. Two low index trenches ($n_L$) are created around the circular core region, namely $M_1$ and $M_3$, which made by pure silica material for reducing fabrication difficulty. The light brown region is represented as $M_2$ and $M_4$ region with high refractive index region ($n_c$) whose RI = 1.451. It is worked as a resonant ring for leaking higher order modes in the segmented cladding region with help of resonant coupling. The four rings of circular MT are introduced with high index of 1.452 ($n_H$) in the core area. The diameter of the circular MT's is r,

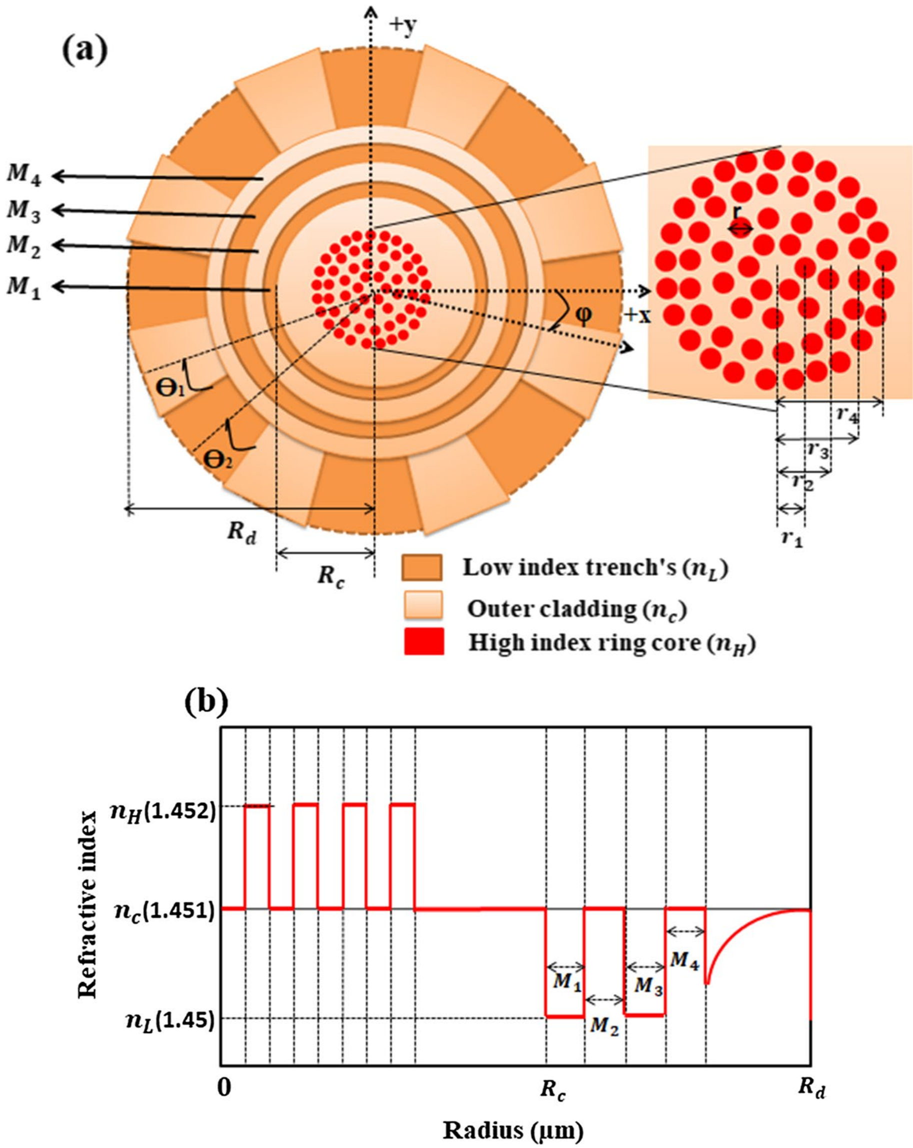


**Fig. 1** **a** cross section and **b** refractive index profile for the high index circular MTSCF

$R_c$ means radius of the core region, and $r_1$, $r_2$, $r_3$ and $r_4$ are the gap from the center of the high index circular MT to the inner most of the core region (see expanded Fig. 1). The circular MT of high index region is used to maintain maximum fundamental mode area ($LP_{01}$) in the core region at the highly bend condition of 7.5 cm. In cladding region, low index ($n_L$) and high index medium ($n_c$) are angularly and regularly segmented for obtaining large mode area with SM operation. $2\theta_1$ and $2\theta_2$ is denoted by angular width of the low index ($n_L$) and high index ($n_c$) medium, respectively.

Generally, bending loss is controlled greater than 1dB/m for higher order modes and less than 0.1 dB/m for fundamental mode for attaining SM operation (Li et al. 2009). The distortion of the refractive index profile ($n_{eq}$) caused by bend can be expressed by following formula (Jain et al. 2013),

$$n_{eq}(r,\phi) = n_0(r,\phi) * \sqrt{1 + \frac{2r}{\rho R_b}\cos\phi} \tag{1}$$

Where, $R_b$ is the bending radius, Φ is the bend orientation angle, $n_0(r,\phi)$ is RI in straight case, and $\rho$ is represented by stress factor whose value is 1.25. The proposed high index circular MTSCF can be fabricated by stack and draw method.

## 3 Properties of the MTSCF

In this study, we use the fully vectorial finite element method to analyze the bending characteristics of the suggested high index circular MTSCF model with suitable perfectly matched layer (PML). The essential characteristics for LMA fibers such as effective mode area (EMA) and confinement loss (CL) is calculated by (Wang et al. 2013),

$$\mathrm{EMA} = \frac{\left(\iint |E|^2 \mathrm{d}x\mathrm{d}y\right)^2}{\iint |E|^4 dxdy} \tag{2}$$

$$\mathrm{CL} = \frac{20}{\ln 10} k_0 \mathrm{Im}\left(n_{\mathrm{eff}}\right) \tag{3}$$

where $k_0 = \frac{2\pi}{\lambda}$ and $\mathrm{Im}\left(n_{eff}\right)$is the imaginary part of effective refractive index of the mode. The optimized parameters of the proposed fiber is $r_1$ = 3 μm, $r_2$ = 6 μm, $r_3$ = 10 μm, $R_C$= 36 μm, r = 1 μm, $M_1$= 9 μm, $M_2$ = 10 μm, $M_3$ = 8 μm, $M_4$ = 8 μm, $R_d$ = 109 μm. Another one important parameter for SM operation is loss ratio. It is stated as the ratio between lowest loss of the higher order mode and loss of the fundamental mode. Typically loss ratio (LR) is greater than 100 sufficient for SM operation. Meanwhile, shorter fibre lengths are sufficient to strip off higher order modes because the lowest loss of higher order mode is > 1 dB/m.

$$\text{Loss ratio(LR)} = \frac{\text{Lowest loss of higher order modes}}{\text{Loss off undamental mode}} \tag{4}$$

## 4 Results and analysis

### 4.1 Effect of multi trench

In the proposed fiber, we have achieved bending loss constraints through low index trenches ($M_1$ and $M_3$). Figure 2 shows the variation of bending loss and effective mode area with respect to $M_1$. The black, green and the red curves are represented the bending loss for the $LP_{01}$, $LP_{11\text{-even}}$ and $LP_{11\text{-odd}}$ mode, respectively. The effective mode area for $LP_{01}$ mode is represented by dotted blue line. When the $M_1$ thickness increases from 7 to

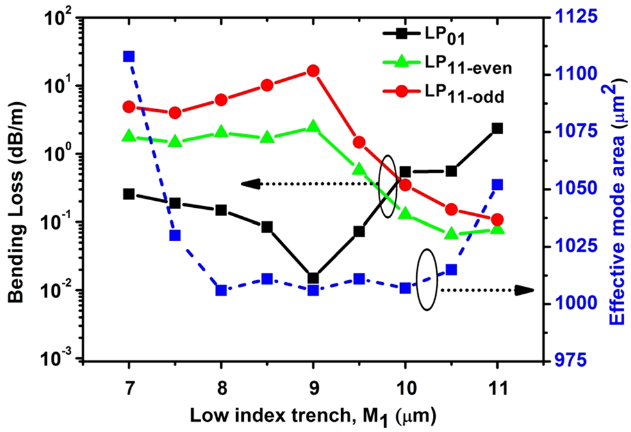


**Fig. 2** Bending loss of $LP_{01}$, $LP_{11\text{-even}}$ and $LP_{11\text{-odd}}$ and mode area of $LP_{01}$ by varying $M_1$

11 μm, the $LP_{01}$ mode decreases upto 9 μm and then increases. Similarly, $LP_{11\text{-even}}$ and $LP_{11\text{-odd}}$ mode increases upto 9 μm and then decreases. The effective single mode operation obtained at M1 thickness of 9 μm, such as loss of $LP_{01}$ is 0.015 dB/m, $LP_{11\text{-even}}$ is 2.435 dB/m and $LP_{11\text{-odd}}$ is 16.45 dB/m. And also the effective mode area of ~ 1000 μm² is attained over the range of 8 to 10 μm.

Similarly, bending characteristics are analyzed with respect to $M_3$ as shown in Fig. 3. The $M_3$ also is supported to effective light fundamental mode confinement in the core region with BL constrains. With help of $M_3$ low index trench, we can easily achieved suppression of higher order modes. In Fig. 3, SM operation obtained at $M_3$ of 8 μm with maintained LMA of ~ 1000 μm². Further, the proposed fiber obtained LR of 162 for effective single mode propagation.

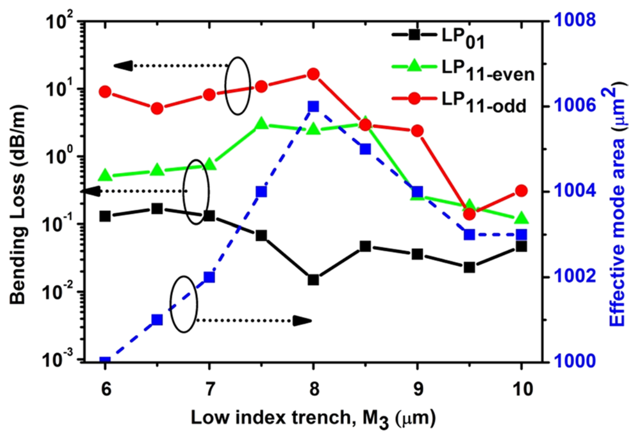


**Fig. 3** Bending loss of $LP_{01}$, $LP_{11\text{-even}}$ and $LP_{11\text{-odd}}$ and mode area of $LP_{01}$ by varying $M_3$

### 4.2 Effect of high index circular MT

We have considered four layer of high index circular MT in the core area for effective mode field distribution in the core area at the bending condition of 7.5 cm. We have indicated in the Sect. 2, $r_1$, $r_2$, $r_3$ and $r_4$ represent distance from high index circular ring to the center of the fiber and also its initial values.

Figure 4 represents the intensity distribution of $LP_{01}$ mode under various layers with different bending conditions. At 15 cm and 7.5 cm bending radius, maximum amount of light is distributed in the four layer of high index circular MT than two and three layer of circular MT (See Fig. 4c and f). The effective mode area for a two, three, and four-layer of high index circular ring, respectively, is 1045 μm$^2$, 1008 μm$^2$, and 915 μm$^2$ (see Fig. 4a, b, and c). Similarly, the mode area for tight bending radius of 7.5 cm is 911 μm$^2$, 950 μm$^2$ and 1006 μm$^2$ for two, three and four layer of high index circular MT (see Fig. 4d, e, and f). Since, we have obtained maximum effective area of 1000 μm$^2$ at compact bending radius of 7.5 cm with help of high index circular MT. Further, we examined the effects of the placement of the circular high index MT. The innermost layer of the high index circular core trench is crucial for mode field scaling in terms of mode field area because it can direct the mode field to the left, increasing mode field area as $r_1$ decreases. The mode area is 1038 μm$^2$ at a bend radius of 7.5 cm when $r_1 = 2$ μm, and it decreases to 998 μm$^2$ when $r_1 = 5$ μm, as can be seen in Fig. 5. But, difficult to leak out the $Lp_{11\text{-odd}}$ mode from the core region at $r_1 = 2$ μm. Finally, we have obtained SM condition at $r_1 = 3$ μm with optimum effective area of 1006 μm$^2$.

Then, we have analyzed bending characteristics for fundamental mode and higher order modes with respect to $r_2$ and $r_3$ as shown in Fig. 6. When $r_2$ and $r_3$ is varied from 6 to 7.5 μm and 8 to 12 μm, respectively, the bend loss is $<0.1$ dB/m for $LP_{01}$ and $>1$ dB/m for $LP_{11\text{-odd}}$, indicating that the bend loss complies with the requirements of single mode operation. Then, $LP_{11\text{-even}}$ mode is 2.45 dB/m for $r_2 = 6$ μm and $r_3 = 10$ μm. Further, mode area of fundamental mode decreases with increases of $r_2$ and $r_3$. So, we have considered optimum effective area of 1006 μm$^2$ with SM condition at $r_2 = 6$ μm and $r_3 = 10$ μm.

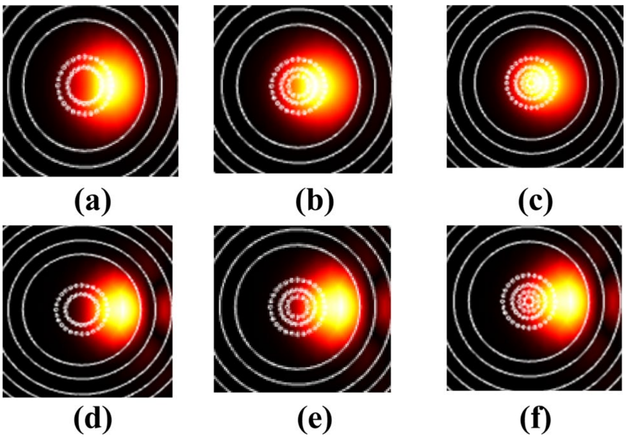


**Fig. 4** Intensity distribution of $LP_{01}$ mode under various layers with different bending conditions. **a** $r_3$ and $r_4$ **b** $r_2$, $r_3$, $r_4$ and **c** $r_1$, $r_2$, $r_3$, $r_4$ at 15 cm bending radius. **c** $r_3$ and $r_4$ **d** $r_2$, $r_3$, $r_4$ and **e** $r_1$, $r_2$, $r_3$, $r_4$ at 7.5 cm bending radius

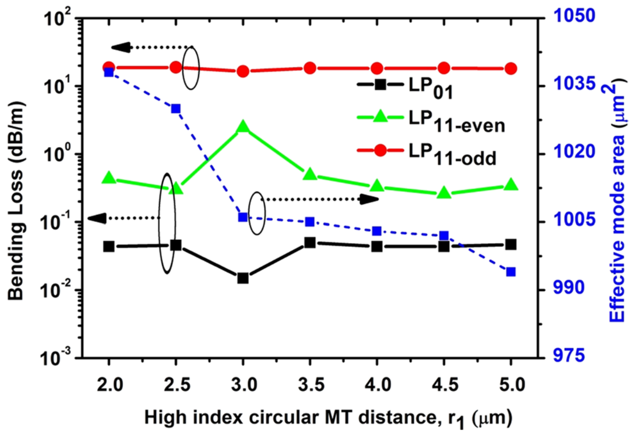


Fig. 5 Bending loss of $LP_{01}$, $LP_{11\text{-even}}$ and $LP_{11\text{-odd}}$ and effective mode area of $LP_{01}$ by varying $r_1$

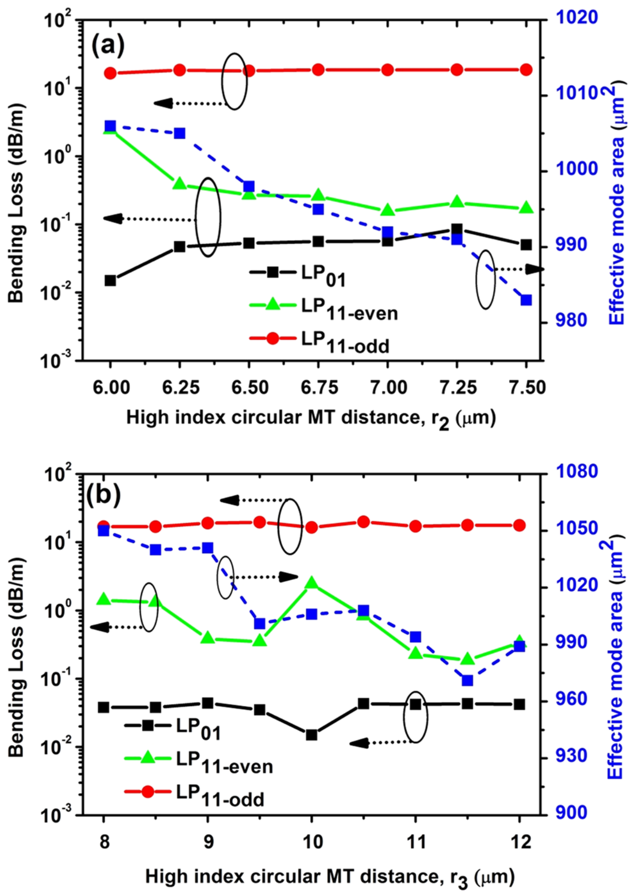


Fig. 6 Bending loss of $LP_{01}$, $LP_{11\text{-even}}$ and $LP_{11\text{-odd}}$ and effective mode area of $LP_{01}$ by varying **a** $r_2$ and **b** $r_3$

Additionally, Fig. 7 illustrates the effect of core radius ($R_c$) on bending loss and mode area at the 7.5 cm bending radius. When $R_c$ range between 34.5 and 36 µm, the fundamental mode and higher order modes are controlled for obtaining maximum mode area with SM operation. The direction of bending causes the mode area to increase as $R_c$ rises from the lowest to the maximum. When proposed fibre is bent along the $+x$ axis, its refractive index typically increases along the $+x$ axis and decreases along the $-x$ axis.

### 4.3 Effect of bending orientation angle

In general, more complex fibre coiling derives from the greater freedom over bend orientation angle. It is crucial to keep in mind that the proposed fibre is suggested for the constrained practical bending radius of 7.5 cm. In order to achieve LMA with bending loss constraints, the suggested fibre is worked up to a 10° bending orientation angle. Within 10°, bending loss of $LP_{01}$ and $LP_{11\text{-odd}}$ is 0.061 dB/m and 1.321 dB/m, respectively as shown in Fig. 8a. Further, optimum mode area and power fraction in core for $LP_{01}$ is 1006 µm$^2$ and 97.48% with bending loss constrains as shown in Fig. 8b.

### 4.4 Effect of duty cycle

By adjusting the duty cycle in SCF, the leakage losses of the core modes are changed. The investigation of how the duty cycle affects the characteristics of the high index circular MTSCF is crucial for design improvement. Duty cycle can be calculated by $\gamma = 1\text{-}\Theta/(360/N)$, where N is represented number of segments. In the proposed fiber, we have considered N = 8. Figure 9 represents the bending loss and mode area with respect to duty cycle. When $\gamma$ range between 0.4 and 0.8, the $LP_{01}$ loss is <0.1 dB/m and $LP_{11\text{-odd}}$ is >1dB/m and mode area is ~1000 µm$^2$. Hence, the proposed fiber provides adequate segment fabrication tolerance. Further, loss ratio of >40 with SM condition can be achieved when $0.4 \leq \gamma \leq 0.8$.

Finally, we have obtained large mode area of 1006 µm$^2$, Loss ratio of 162 and SM operation at tight bending radii of 7.5 cm and optimized parameters are $r_1 = 3$ µm, $r_2 = 6$ µm,

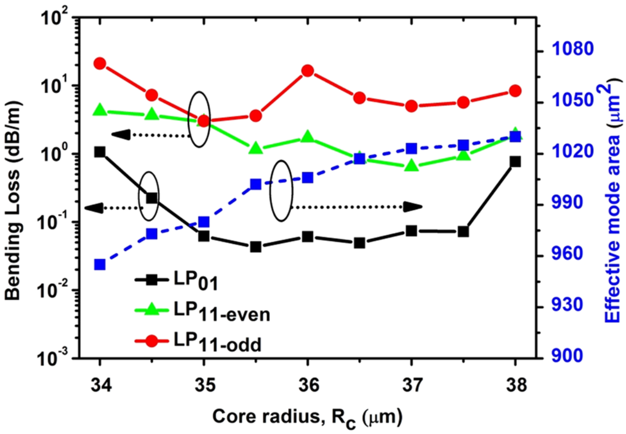


**Fig. 7** Bending loss of $LP_{01}$, $LP_{11\text{-even}}$ and $LP_{11\text{-odd}}$ and effective mode area of $LP_{01}$ by varying $R_c$

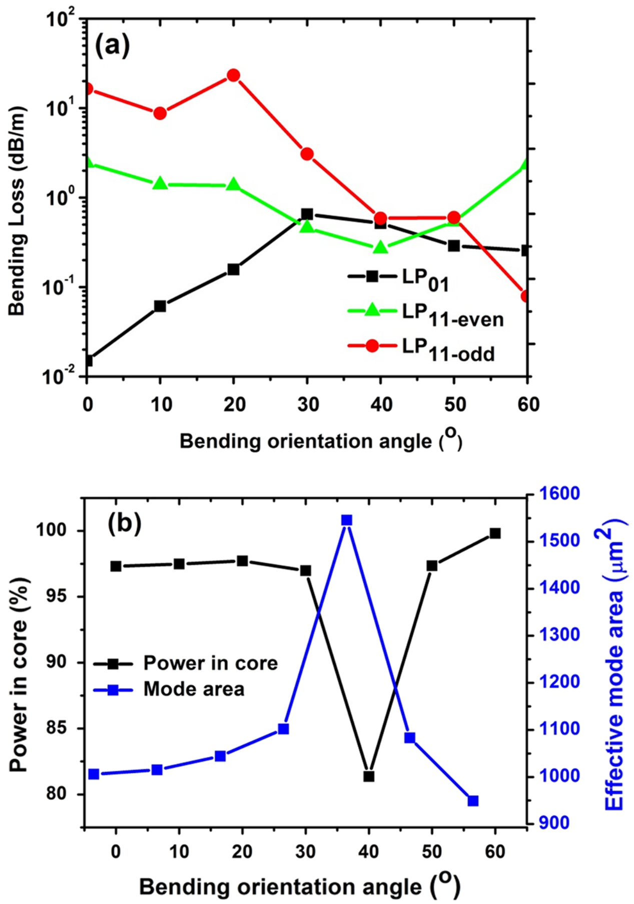


**Fig. 8** **a** bending loss for fundamental mode and higher order modes and **b** power in core and mode area for fundamental mode by varying bending orientation angle

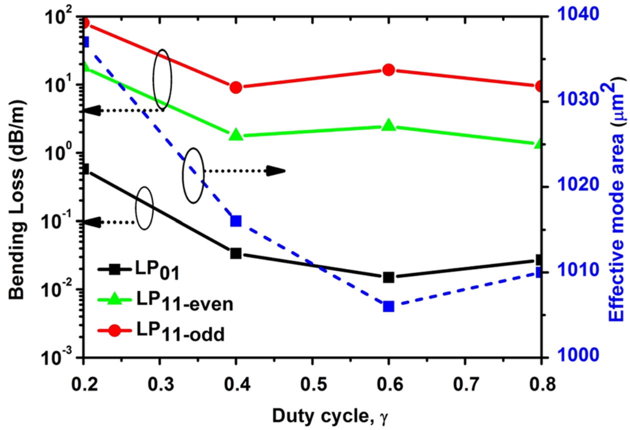


**Fig. 9** Variation of bending loss and effective mode area by varying duty cycle

**Table 1** Comparison of various existing LMA fibers with proposed MTSCF fiber

| Designs | Bending radius (cm) | Fundamental mode loss (dB/m) | Lowest higher order mode loss (dB/m) | Loss ratio | SM operation | Mode area ($\mu m^2$) |
|---|---|---|---|---|---|---|
| SCF (Ma et al. 2016) | 10 | 0.017 | 0.23 | 13.5 | No | 754 |
| SR-SCF (Ma et al. 2017) | 30 | 3.920 | 28.20 | 7.2 | No | 1002 |
| PTA-SCF (Wang et al. 2020) | 20 | 0.228 | 5.80 | 25.4 | No | 1041 |
| HIRRR-SCF (Guo et al. 2021) | 15 | 0.092 | 4.08 | 45.6 | Yes | 1018 |
| N-SCF (Ma et al. 2018) | 15 | 5.12E-4 | 1.68 | 1650 | Yes | 212 |
| Proposed MTSCF | 7.5 | 0.015 | 2.435 | 162 | Yes | 1006 |

$r_3 = 10$ μm, $R_C = 36$ μm, $r = 1$ μm, $M_1 = 9$ μm, $M_2 = 10$ μm, $M_3 = 8$ μm, $M_4 = 8$ μm, $R_d = 109$ μm. Further, regarding bending radius, loss of fundamental and lowest higher order mode, loss ratio, SM operation and mode-area, Table 1 shows the comparison of various existing LMA fibers with proposed MTSCF fiber in detail.

## 5 Conclusion

We have proposed bend resistant segmented cladding fiber with four layer of high index circular multi trench in the core region to obtain SM operation with maximum effective mode area at practical bending condition. The performance of the proposed fiber is investigated in relation to high index circular multi trenches, low index trenches, duty cycle and bending orientation angle. The obtained mode area is 1006 $\mu m^2$ with SM condition at tight bending radius of 7.5 cm. Moreover, loss ratio between fundamental mode ($LP_{01} = 0.015$ dB/m) and lowest higher order mode ($LP_{11\text{-odd}} = 2.435$ dB/m) is 162, which is confirmed effective single mode operation. It has been shown to have excellent higher order mode and bending-immune suppression performance. To simplify fabrication, pure silica-based low refractive index trenches are added around the core region. The suggested high index circular MTSCF designs are an appropriate option for high-power compact fibre laser systems.

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**Author contributions** SE, and NA contributed to designing the model through simulation software and also written manuscript. The first draft of the manuscript is written and also verified results by GTR and FAA. All authors read and approved the final manuscript.

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**Data availability** Data sharing not applicable to this article as no datasets were generated or analyzed during the current study.

## Declarations

**Conflict of interest** The authors declare no competing interests.

**Ethics approval** This study complies with ethical standard.

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