Bending performance of large mode area multi-trench fibers

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Abstract: Bending performance of the Multi-trench Fibers (MTFs) has been investigated using the Finite Element Method. Numerical investigations show that MTFs can provide low-loss effective single mode operation under bent configuration, thanks to the resonant coupling of the Higher order Modes (HOMs). Large ratio between the HOMs and the Fundamental Mode (FM) losses can be ensured, although the ratio drops with increasing Effective Area (A_{eff}) of the FM. MTFs provide better losses ratio between the HOMs and the FM in comparison with other fibers like step-index, W-type, and parabolic fibers.

OCIS codes: (060.2280) Fiber design and fabrication; (140.3510) Lasers, fiber.

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1. Introduction

High power fiber lasers have realized their potential over the last decade. Power level of fiber lasers has already crossed the 10kW level [1]. However, non-linear effects impose serious constraints on power scaling. One way to mitigate these effects is to increase the Effective Area (A_{eff}) of the fundamental core mode and reduce the length of the fiber laser, which increases the threshold power level for stimulated non-linear effects.

However, it is difficult to increase the A_{eff} while preserving single-mode propagation in order to have a good beam quality. Moreover, it has recently been found that presence of Higher Order Modes (HOMs) in fiber lasers and amplifiers can cause detrimental modal instability at high power [2]. The impact of the bend also becomes stronger with increasing A_{eff} [3]. One approach to avoid the bend-induced effects, while ensuring single-mode operation with large A_{eff}, is to use the Rod-type fibers. Rod-type fibers are a few mm thick and cannot be bent [4]. These fibers offer single-mode operation for ultra large mode-area. However, this kind of a rod-type fiber laser may not be suitable for many applications because of a relatively large device size and lower operational flexibility. Hence, researchers are trying to develop the fiber designs which can show single-mode operation for a large mode area along with good bend robustness. Several structures have been proposed that maintain effective single mode operation for large mode area by offering larger losses to the HOMs compared to the Fundamental Mode (FM), e.g. low-NA Step Index Fibers (SIFs) [5, 6], Photonic Crystal Fibers (PCFs) [7], Leakage Channel Fibers (LCFs) [8], 2-D All Solid Photonic Band Gap Fibers (2D-ASPBGFs) [9], Bragg fibers [10], and tailored cladding fibers [11].

Low-NA SIFs, which work on elimination of the HOMs by bend-induced filtering, have shown good potential for mode area scaling [5, 6]. Their performances are limited by the decreasing losses ratio between the HOMs and the FM with increasing area [6]. PCFs are also a new approach of large mode area scaling [7]. However, they require complex fabrication process like stack and draw technique. Moreover, the presence of air-holes leads to numerous practical difficulties. LCFs, which are a modified form of the PCFs, offer better mode area scaling than PCFs but have poor losses ratio between the HOMs and the FM [3, 8]. Recently, mode-area scaling of 2-D ASPBGFs has been proposed [9]. However, their fabrication is complex and expensive. Moreover, these fibers suffer from reduced cladding-pumping efficiency due to the presence of high index rods in the cladding. Fibers having tailored cladding for HOMs suppression are also limited in mode area scaling [11].

Bragg fibers have shown large mode area scaling capability and offer the advantages of good bend-robustness and easy fabrication process [10, 12, 13]. However, the presence of the high-index rings in the Bragg fiber can cause unwanted couplings between the core and the high-index ring modes due to slight imperfections in the realized fibers [14]. Moreover, these high-index rings do not allow the Stress Applying Parts (SAPs) to be put outside of the core region, which makes the realization of a polarization maintaining Bragg fiber difficult. On the other hand, by placing the SAPs inside the core of the Bragg fiber, a single-polarization Bragg fiber has been demonstrated. However, this dramatically reduces the A_{eff} of the FM [14].

Recently, we proposed a new structure, the Multi-trench fibers (MTFs), for mode area scaling of rod-type fibers [15]. Thanks to their cylindrical symmetry, these fibers offer advantages such as easy fabrication and preservation of beam quality in the presence of small

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core index-depression (better than in the case of large-pitch PCFs (LPFs)) [15]. Moreover, there are no high-index rings in the MTFs, so it should be free from any unwanted couplings due to imperfections in the realized fibers. In this paper, we investigate the potential of MTFs for compact fiber lasers and beam delivery applications.

2. Multi-trench fiber

Figure 1(a) shows the schematic cross section of the MTF structure. Figure 1(b) shows the schematic of refractive index profile of the MTF and also presents the notations used in this paper: r_c is the core radius, t is the thickness of all the low-index rings (trenches), d_1 and d_2 are the thicknesses of the first and the second high-index rings (resonant rings), and Δn is the refractive index difference between the core and the trenches.

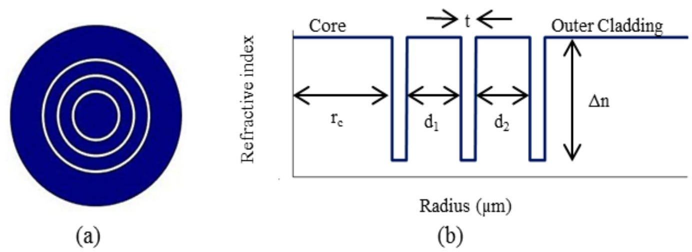

Fig. 1. (a) Schematic cross-section of the MTF. Blue and white colours represent high and low-refractive index regions respectively. (b) Schematic of refractive index profile of the MTF.

Numerical simulations on MTFs have been performed with a full-vectorial Finite Element Method (FEM), in which the domain truncation has been ensured by using the circular anisotropic Perfectly Matched Layer (PML). All the calculations presented in this paper are at 1.06μm wavelength.

3. Design of 30μm core MTF in straight and bent condition

The leakage losses of the FM and the first four HOMs of a 30μm diameter core fiber, with t = 2μm and Δn = 0.006, as a function of thickness of the resonant ring (assuming both resonant rings thicknesses to be the same, i.e. $d_1 = d_2 = d$) are shown in Fig. 2(a). All the modes of the core are leaky due to their resonance coupling with the resonant rings modes. In order to ensure, a single-mode operation of the core, we need to ensure high losses for the HOMs of the core by resonant couplings to the resonant rings modes as compared to the FM modes. It is well known that for a complete resonant coupling to take place between two leaky modes, there are two basic conditions to satisfy. First one is the phase matching and second one is the loss matching of two leaky modes under coupling [16].

It is worth noting that the effective indices of the HOMs of the core are different, so it is impossible to fulfill both of these conditions completely for all the relevant HOMs of the core at a single thickness of the resonant ring. However, the thickness of the resonant ring can be chosen in such a way that all the relevant HOMs sustain sufficient leakage losses for effective single mode operation as shown in Fig. 2(a). The leakage losses of the FM are smaller than 0.0045dB/m for all the studied resonant ring thicknesses (5μm to 10μm) and the LP_{11} leakage losses remain larger than 1dB/m for resonant ring thickness from 8.5μm to 10.0μm. The leakage losses of all the other HOMs of the core (we have considered all the possible HOMs of the core, although the losses of only few of them have been shown in Fig. 2(a)) are larger than 1.5dB/m for all the studied resonant ring thicknesses. The leakage losses of the HOMs can be increased by decreasing the trench thickness (t), or the refractive index difference of trench (Δn) as observed in the design of the 100μm and 140μm diameter core MTFs [15].

Bending losses of the MTF can be analyzed using standard conformal mapping [17] with additional stress perturbations [18] by following the standard equation:

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$$n^2_{eq}(r,\varphi) = n^2(r)*\left(1+\frac{2r}{\rho R}\cos\varphi\right), \tag{1}$$

where n(r) is the index profile of the unbent fiber, R is the bend radius, φ is the azimuthal angle, and ρ (here fixed to 1.25) has been included to take account of the stress factor. Inset of Fig. 2(b) shows the obtained equivalent refractive index profile of the MTF shown in Fig. 1(b) for d = 8μm, Δn = 0.006, t = 2μm, at a bend radius of 15cm using the above equation. It is clear from the equivalent profile of the fiber that, under the bent case the effective indices of the core and the ring modes change, and in turn the conditions of phase matching for resonance coupling also change. Figure 2(b) shows the bending losses of the LP_{01} and the LP_{11} modes (including both polarizations of the LP_{11} mode) of the core as a function of the resonant ring thickness. The losses in the bent case are large compared to the unbent case due to the bend-induced coupling with the resonant rings. Figure 2(b) shows the large losses for the LP_{11} mode (from 4dB/m to 14dB/m) for the resonant ring thickness from 8.0 to 8.5μm.

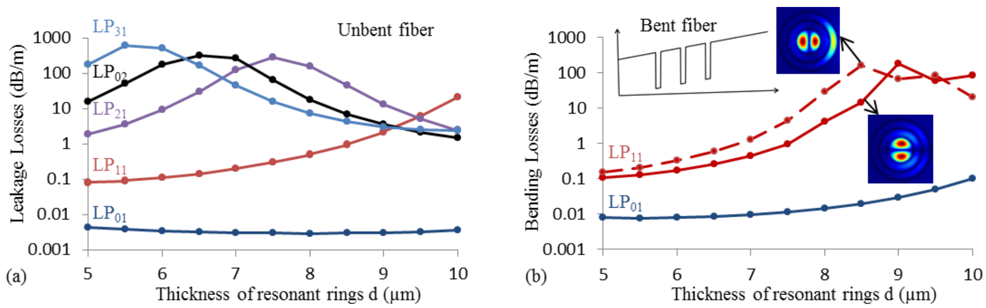

Fig. 2. Losses of the FM and the few HOMs in (a) unbent (b) bent fiber at 15cm bend radius as a function of the resonant ring thickness of the fiber having r_c = 15μm, t = 2μm, and Δn = 0.006.

From a perspective of fabrication, we studied the unitless ratio of lowest losses level of the HOMs, expressed in dB/m, (considering all the HOMs and their polarizations as well) to the FM losses, expressed in dB/m, as a function of the resonant ring thickness. We have considered the mismatch of both the resonant rings thicknesses since it is unlikely to obtain exactly the same thickness of both the resonant rings in a fabricated fiber. Figure 3(a) shows the ratio of lowest losses level of the HOMs to the FM losses for different thicknesses of the resonant rings of the fiber with r_c = 15μm, t = 2μm, and Δn = 0.006 at 15cm bend radius. X-axis shows the thickness of the first resonant ring (d_1). Y-axis shows the relative thickness of the second resonant ring (Y), whereas absolute thickness of the second resonant ring is d_2 = 2*Y-d_1. For example in Fig. 3(a), for a first resonant ring thickness (d_1) of 8μm, Y varies from 8μm to 8.5μm, so the absolute thickness of the second resonant ring (d_2) varies from 8μm to 9μm. Similarly for d_1 = 8.5μm, Y varies from 8μm to 8.5μm which corresponds to second ring thickness (d_2) from 8μm to 8.5μm. Figure 3(b) shows the losses ratio for the similar fiber as in Fig. 3(a) but for a different Δn = 0.005. Figures 3(c) and 3(d) show the corresponding losses of the FM. It can be observed that for Δn = 0.006, the FM losses vary from 0.014dB/m to 0.022dB/m, the losses ratio varies from 168 to 394, and the HOMs lowest losses vary from 2.35dB/m to 7dB/m. Similarly for Δn = 0.005, the FM losses vary from 0.06dB/m to 0.1dB/m, the losses ratio varies from 162 to 317, and the HOMs lowest losses vary from 12dB/m to 22dB/m. From Figs. 3(c) and 3(d), we can conclude that slight variations of the refractive-index have stronger impact on the FM and the HOMs losses than their losses ratio. This result is in good agreement with those of the earlier study of the rod-type MTFs [15]. Similarly, we have observed that a slight increase and decrease of the trench thickness has stronger impact on the FM and the HOMs losses than their losses ratio. We have omitted, here, the details of these results (impact of trench thickness on the losses of the

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core modes), due to their similarity with those obtained in the unbent case [15]. We can see from these calculations that a good losses ratio between the HOMs and the FM, which is an important property for the fiber lasers and for beam-delivery applications, can be obtained from a 30µm diameter core MTF. Moreover, this high ratio can be obtained for a wide range of bend radius, which is also a desired feature for numerous applications.

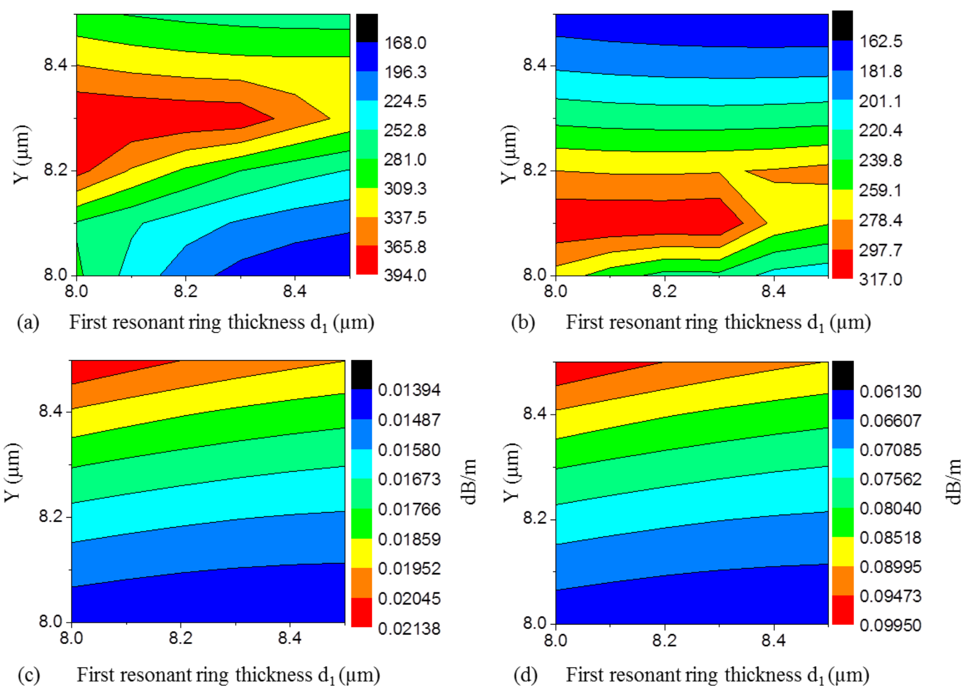

Fig. 3. Ratio of the HOMs lowest losses level to the FM losses for different combinations of the first and the second resonant rings thicknesses for 30µm diameter core fiber with t = 2µm (a) Δn = 0.006 (b) Δn = 0.005. (c) and (d) shows the respective FM losses for these fiber parameters. X-axis presents thickness of the first resonant ring (d_1) and Y-axis presents a parameter Y, where thickness of the second resonant ring is equal to $d_2 = 2*Y-d_1$. All Figs. has its own color scale.

We chose two sets of cladding parameters for the 30µm diameter core fiber (d = 8.0µm, Δn = 0.006 and d = 8.5µm, Δn = 0.005) at a fixed t = 2µm to further investigate the bend radius range for high losses ratio. These two sets of cladding parameters, present two extreme cases (lowest and highest) of the FM losses among d = {8.0µm-8.5µm} and Δn = {0.005-0.006} at a fixed t = 2µm. The first case (d = 8.0µm, Δn = 0.006) presents lowest FM losses; we call it the best case and the second case (d = 8.5µm, Δn = 0.005) presents highest FM losses; we call it the worst case. Figure 4(a) shows the FM losses and the HOMs lowest losses level for 8cm to 40cm bend radius for both the cases. Figure 4(b) shows the A_{eff} of both the fibers over the bend radius range, which varies from 380µm^2 to 417µm^2. It is interesting to note that the worst case offers a range of 15cm to 28cm, fulfilling the criterion of the FM losses smaller than 0.1dB/m and the HOMs losses larger than 10dB/m, while the losses ratio varies from 162 to 440. It is worth noting that, this is a strongly recommended criterion for single mode operation for fiber laser applications [6]. On the other hand, the best case offers a range of 18cm to 28cm bend radius, fulfilling the criterion of the FM losses smaller than 0.01dB/m and the HOMs larger than 1dB/m, while the losses ratio varies from 200 to 320. It is important to note that this criterion would be sufficient for single-mode low-loss operation for several beam delivery applications (passive fibers). In unbent case, FM losses and HOMs

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lowest losses are 0.012dB/m and 4.41dB/m respectively with FM A_{eff} of 418.46μm^2 for worst case and FM losses and HOMs lowest losses are 0.003dB/m and 0.5dB/m respectively with FM A_{eff} of 406.56μm^2 for the best case.

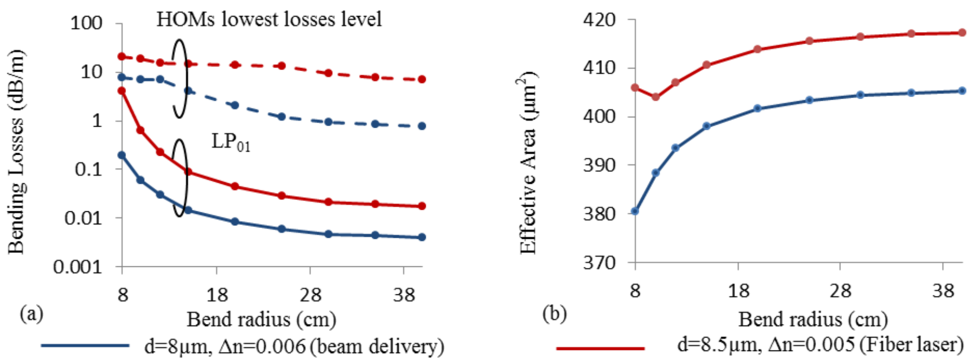

Fig. 4. (a) Losses of the FM and the lowest losses level of the HOMs as a function of the bend-radius (b) A_{eff} of the fundamental core mode as a function of the bend radius.

4. Mode area scaling to 40μm and 46μm diameter core

To scale up the mode area further, we studied 40μm and 46μm diameter core MTFs with t = 1.6μm and Δn = 0.006 at 20cm bend radius. Figures 5(a) and 5(b) show the ratio of the HOMs lowest losses level to the FM losses and the losses of the FM respectively, for different combinations of the first and second resonant ring thicknesses of 40μm diameter core fiber. For large numbers of combinations of the resonant ring thicknesses shown in Figs. 5(a) and 5(b), the FM losses vary from 0.033dB/m to 0.099dB/m, while the losses ratio varies from 49 to 203. Figure 5(a) also shows a region covered by the dashed white line, which corresponds to the thicknesses of both the resonant rings varying from 10μm to 11μm. For these combinations of the thicknesses, the FM losses vary from 0.034dB/m to 0.075dB/m, while the losses ratio varies from 49 to 130, and the A_{eff} is larger than 650μm^2. On the other hand, for certain combinations of ring thicknesses (shown in dark blue in Fig. 5(a)), the FM losses goes high up to 0.21dB/m and the losses ratio drops below 30. For these combinations, the second resonator thickness is large enough (from 12.5μm to 13μm) to induce the coupling between the FM and the second resonant ring modes, which in turn induces high losses to the FM. Figure 5(c) shows the ratio of the HOMs lowest losses level to the FM losses for 46μm diameter core. Over the large numbers of combinations of the resonant ring thicknesses, the FM losses remain smaller than 0.12dB/m (shown in Fig. 5(d)), while the losses ratio varies from 30 to 131, and the A_{eff} exceeds 790μm^2.

Fini et al. have reported a comparative analysis of the losses ratio between the FM and the HOMs lowest losses for a fixed FM losses of 0.1dB/m, for four different fiber design parabolic fibers, SIFs, W-type, and LCFs [3]. Analysis shows that the parabolic fibers offer best leakage losses ratio, which is smaller than 200 for A_{eff} 400μm^{2}and 20 for A_{eff} 700μm^2. Our study in section 3 and 4 shows that the MTFs can offer better leakage losses ratio (i.e. 162 to 317 for A_{eff} 400μm^2 and larger than 30 for A_{eff} 790um^2 for a fixed FM losses of 0.1dB/m) compared to the parabolic fibers. On the other hand, MTFs show significantly larger bend radius range, which is difficult to achieve in case of the SIFs and the parabolic fibers.

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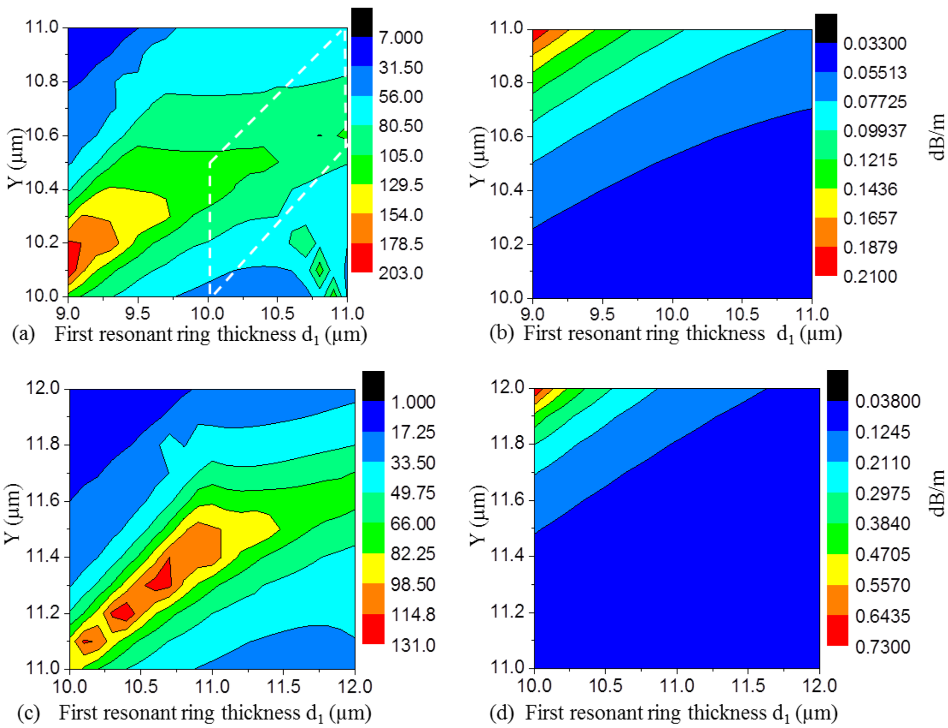

Fig. 5. (a) and (c) Ratio of the HOMs lowest losses level to the FM losses for different combinations of the first and the second resonant rings thicknesses for 40μm and 46μm diameter core fibers respectively with t = 1.6μm and Δn = 0.006 at 20cm bend radius (b) and (d) shows the respective FM losses for these fiber parameters. X-axis presents the thickness of the first resonant ring (d_1) and Y-axis presents a parameter Y, where the thickness of the second resonant ring is equal to $d_2 = 2*Y-d_1$. All Figs. has its own color scale.

5. MTF in double clad configuration

In order to exploit the high pump power for laser applications, a fiber needs to have a double clad configuration. However, in the double clad configuration, effective leakage losses of the core modes are zero, as the outermost layer is either a low index polymer coating or an air-clad jacketing. This is very different from what one assumes while calculating the leakage losses of the core modes by using a PML around the fiber. Although, in reality, we have a polymer coating or an air-clad jacketing instead of the PML, which can reflect back light to core, we neglect this effect in our calculations. That is why, in a double clad configuration, leakage losses might not present the true suppression of the HOMs. Nevertheless, computed leakage losses in previous works have been proved to be a useful criterion for single-modedness. Recently, G. Gu et al. showed that a non-circular cladding-polymer interface helps in increasing HOMs losses and can provide HOMs losses approximately equal to the losses calculated using a PML [19].

It is worth noting that, in a double clad configuration, the lower power fraction of the HOMs in the core region (assuming the entire core is doped with rare-earth ions) as compared to the power fraction of the FM in the core region can also be another useful criterion for single mode operation. We calculated the power fraction of the HOMs and the FM in the core for different parameters of MTF, assuming a polymer coating of refractive index 1.35. MTF offers reduced overlap of the HOMs with the core region as compared to the FM. For example, for r_c = 15μm, t = 2μm, and d = 8μm at 15cm bend radius, for different refractive index difference between the core and the trench: Δn = 0.005, 0.0045, and 0.004, the power fraction of the HOMs in the core is smaller than 0.86, 0.82, and 0.67 respectively, while the power fraction of the FM remains larger than 0.98.

6. Conclusion

We theoretically investigated the bending behavior of the MTFs at 1.06μm. MTFs with a core diameter of 30μm ensuring HOMs losses larger than 10dB/m and 1dB/m and the FM losses smaller than 0.1dB/m and 0.01dB/m respectively, over wide range of bend radius have been achieved. The A_{eff} of the FM remains larger than 380μm^2. Furthermore, the mode area scaling to 790μm^2 for a 46μm core diameter at 20cm bend radius has been achieved but at the expense of reduced losses ratio between HOMs and FM. MTFs ensure better HOMs suppression than other fiber structures like Parabolic, SIFs, and W-type fibers.

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