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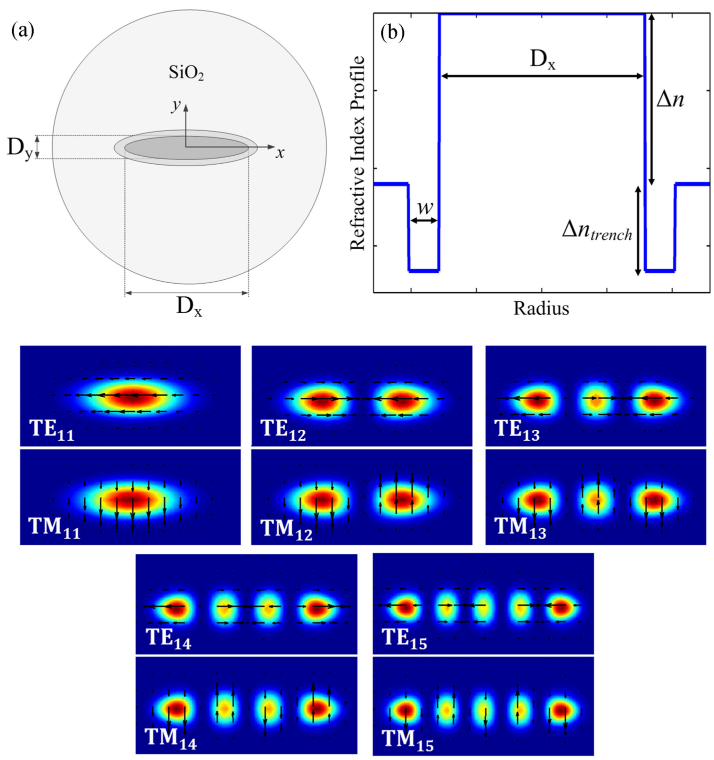

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Design of Highly Elliptical Core Ten-Mode Fiber for Space Division Multiplexing With 2 × 2 MIMO

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Abstract: In this paper, a weakly coupled few-mode fiber requiring only 2 × 2 multi-in multi-out equalizer blocks, which makes it compatible with standard coherent receivers with polarization diversity. The fiber has a highly elliptical core, surrounded by a depressed index trench in the cladding, and supports five spatial modes with twofold polarization degeneracy (ten channels). The fiber is designed to mitigate inter-modal crosstalk since the effective index difference between spatial modes is larger than $\sim 1 \times 10^{-3}$ over the *C*-band. Through numerical simulations, we report on bending loss and other modal characteristics such as effective area and chromatic dispersion. Finally, we briefly discuss the scalability of the design.

Index Terms: Fiber design, space division multiplexing, few mode fiber.

1. Introduction

In order to meet the demand for unabated growth of data traffic, mode division multiplexing (MDM) has attracted much interest in recent years. In contrast to conventional single-mode fiber (SMF) that supports the transmission of two polarization-multiplexed data channels per wavelength, few-mode fiber (FMF) multiply the fiber capacity by reusing the same carrier wavelength over multiple modes with independent data streams [1]. One of the most critical impairments in MDM transmission is crosstalk between spatial channels. Strategies to mitigate this crosstalk are intricately linked to the optical fiber design. In most MDM experiments, multiple-input multiple-output (MIMO) digital signal processing (DSP) is used to compensate inter-modal crosstalk that occurs between all spatial channels (i.e., full-MIMO) [2]–[6]. As an example, a graded-index fiber with a fluorine-doped trench was used for transmission over 15 spatial channels using 30 × 30 MIMO [6]. Although this approach works effectively even in systems transmitting over strongly-coupled FMF, the MIMO complexity necessary to retrieve the transmitted information increases rapidly with the number of spatial channels [7]. Because large differential mode-group delay (DMGD) directly impacts the size of the sub-equalizers, FMF designs aim at minimizing DMGD [8], [9].

An alternative approach for reducing the DSP complexity is to use weakly-coupled FMF [10]–[13]. In this case, MIMO blocks with relatively low dimensionality are utilized only for compensation of mode-coupling within mode groups, as mode-coupling between different mode groups is prevented by the large effective refractive index difference, Δn_{eff}, between the spatial modes. A small number of modes in each of the well separated mode groups are thus desirable to keep the dimensionality of MIMO blocks low. In this respect, graded-index fibers are not suitable for weakly-coupled FMF because at least two different linearly polarized (LP) spatial modes typically belong to the same mode group (except for LP_{01}). For example, LP_{11a} and LP_{11b} form a degenerate mode group that would require 4 × 4 MIMO equalizers. Similarly, LP_{21} and LP_{02} modes in graded-index fiber constitute a near-degenerate mode group that requires a block of 6 × 6 MIMO equalizers for mode demultiplexing.

Several fiber designs, including step-index FMF [10], [11], step-index ring-core FMF [12], and graded-index ring-core FMF [13], have been used as weakly-coupled FMF. A recent experiment showed the detection of ten LP modes in a weakly-coupled step-index FMF with small MIMO equalizer blocks of 2 × 2 and 4 × 4 [11]. Although these FMFs are designed to suppress mode coupling between dissimilar modes groups, they still present degeneracy between non-rotationally symmetric modes such as LP_{11a} and LP_{11b}. Therefore, the use of at least 4 × 4 MIMO equalizers is required. When a large number of taps (more than several hundreds) are required for higher-order mode groups, a reduction from blocks of 4 × 4 to blocks of 2 × 2 leads to significant savings in DSP.

From a practical point of view, 2 × 2 MIMO is acceptable for a variety of applications since it is widely used for current optical networks (e.g., 100 G optical transport network transponders) to handle polarization-multiplexed signals over SMF. It would therefore be advantageous to design weakly-coupled FMF that exhibits only twofold polarization degeneracy because the needed DSP would become essentially the same as that of standard coherent receivers with polarization-diversity. Recently, the use of elliptical core FMF to break the degeneracy between even and odd modes of non-rotational symmetric modes has been demonstrated [14]–[16]. For example, negligible modal crosstalk among three spatial modes (LP_{01}, LP_{11a} and LP_{11b}) was achieved even under bending [14]. However, the number of the spatial channels was limited due to the difficulty of increasing Δn_{eff} sufficiently to lift the degeneracy between higher-order modes.

In this letter, we propose a highly elliptical core FMF design for MDM transmission using only 2 × 2 MIMO DSP blocks. The fiber supports five spatial modes with twofold polarization degeneracy, for a total of ten channels. The highly elliptical profile has spatial modes that are separated by Δn_{eff} larger than $\sim 1 \times 10^{-3}$, while the core-cladding refractive index difference remains reasonable at only 1.1×10^{-2}. Fiber designs have been proposed to further lift the polarization degeneracy using step-index ring-core [17] elliptical ring-core [18], or PANDA-type elliptical core [19], thus completely eliminating the need for MIMO processing. However, these fibers are typically characterized by high core-cladding index difference (i.e., around 3×10^{-2}) to achieve the target birefringence, δn_{eff}, of $\sim 1 \times 10^{-4}$. This large index step makes low-loss fiber fabrication more difficult [20]. Successful MDM strategies also require the development of low crosstalk mode multiplexers and demultiplexers that are the object of concurrent research efforts [21], [22]. This paper, focused on fiber design, is organized as follows. Section 2 describes the geometry and parameters of highly asymmetric core FMFs. Section 3 reports the impact of core shape on the Δn_{eff} between spatial modes. In Section 4, we optimize the fiber design considering several criteria including effective index difference and bending loss. Section 5 provides numerical simulation results of various characteristics of the optimized highly elliptical FMF. In Section 6, we discuss the scalability of this fiber and conclusions follow in Section 7.

2. Fiber Geometry

The proposed highly elliptical core fiber design is shown in Fig. 1(a). In [23], the authors proposed a rectangular core fiber for mode division multiplexing, which they subsequently characterized in [24]. Such a fiber is shown in Fig. 1(b). In both cases, the large asymmetry allows a single resonance

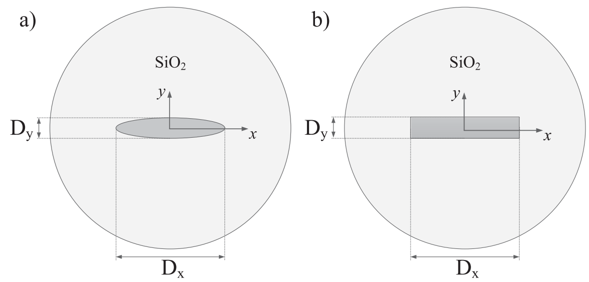

Fig. 1. Cross sections of a: (a) highly elliptical core fiber, and (b) rectangular core fiber. The shaded areas are the fiber cores made of GeO_2-doped silica.

TABLE 1
Fiber Core Dimensions to Support Five Spatial Modes (10 Channels) With $\Delta n = 5 \times 10^{-3}$

Fiber	Width (D_x)	Height (D_y)
Elliptical core	41.0 μm	6.8 μm
Rectangular core	36.4 μm	6.2 μm

along the short axis (*y*-axis) of the core, while the core dimension along the long axis (*x*-axis) controls of the number of modes. Consequently, the intensity profiles of the modes are composed of lobes distributed as a one-dimensional array. In agreement with the nomenclature adopted in [23], we label the spatial modes as TE_{1n} and TM_{1n}, depending on the polarization state (respectively along the *x*-axis or the *y*-axis). The subscript 1 indicates single mode operation along the short axis direction, while *n* is an integer value corresponding to the number of intensity lobes along the long axis. The fundamental modes are thus TE_{11} and TM_{11}. In the discussion below, we first compare the performance of the proposed highly elliptical core fiber (Fig. 1(a)) with rectangular core fiber (Fig. 1(b)). We assume that the cladding is made of silica (SiO_2), i.e., $n_{clad} = 1.444$ at 1.55 μm, and the core is made of silica doped with germanium dioxide (GeO_2) with a step-index profile. The cladding diameter is a standard 125 μm.

The highly elliptical fiber is advantageous from a fabrication point-of-view since it is compatible with modified chemical vapor deposition (MCVD) fabrication techniques. To make such a fiber, we start with a cylindrically symmetric preform made by MCVD. Two slices of the preform are cut along its length on two opposite sides, resulting in two straight, parallel surfaces along the preform longitudinal axis. The preform is then heated to allow surface tension and the flow of material to eliminate the flat surfaces. Consequently, the originally round core becomes elliptical at the end of the process. Since the preform is fabricated with MCVD, the design can include a trench to reduce bending loss.

3. Highly Asymmetric Core Design

As a starting point, the core refractive index is set to $n_{core} = 1.449$, corresponding to approximately a 3.3% molar fraction of GeO_2 in SiO_2 (core-cladding refractive step-index, Δn, of 5×10^{-3}). For ease of comparison, we choose a refractive index step similar to the one in [23] (5.3×10^{-3}). We then adjusted the core dimensions in order to support 10 vector modes in both cases. Table 1 lists the core dimensions of both fibers chosen so that they support 5 spatial modes with two polarizations. The core heights are chosen small enough to guarantee a single resonance along the short core axis. We note that the elliptical core has a longer dimension along the *x*-axis, D_x, than the rectangular core. The elliptical shape of the core decreases the effective index of the modes

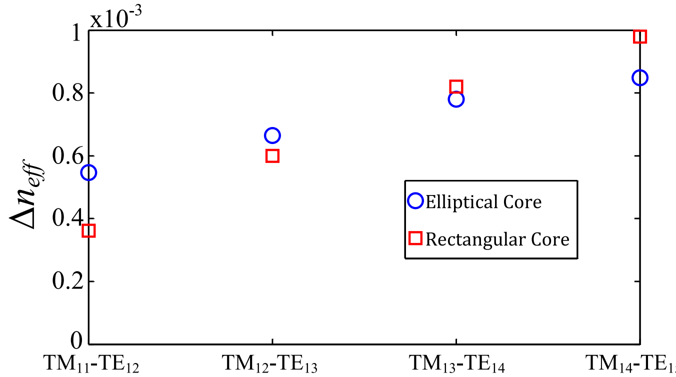

Fig. 2. Effective index difference between the adjacent spatial modes for the two fiber designs: elliptical core (blue circle) and rectangular core (red square). The parameters of the fibers are listed in Table 1.

and, consequently, larger core dimensions are needed for the higher order modes to be guided. Numerical simulations were performed with a finite element solver (COMSOL).

To suppress the modal crosstalk between the spatial modes, a large Δn_{eff} is desirable as shown in the analysis presented in [25] and as observed experimentally in [26], [27]. We numerically calculated the Δn_{eff} between the adjacent spatial modes (i.e., TM_{1n} and $TE_{1(n+1)}$), and Fig. 2 compares the results for the two fiber designs. The lowest Δn_{eff} occurs between the lower order modes that will consequently suffer the most crosstalk and limit the data transmission performance of the fiber. Results show that the highly elliptical core has a higher Δn_{eff}, between these two modes, i.e., 5.4×10^{-4} compared to 3.6×10^{-4} for the rectangular core. The elliptical core, overall, shows a more uniform Δn_{eff} and a higher minimum Δn_{eff}.

It should be noted that neither of these fibers is polarization maintaining. For both fiber designs, the effective index difference between polarization modes (i.e., TM_{1n} and TE_{1n}) or modal birefringence (δn_{eff}), is on the order of 10^{-5}. The minimum birefringence value usually considered to be necessary to maintain polarization is 1×10^{-4} [28]. Both fibers would therefore require 2×2 MIMO to retrieve polarization multiplexed signals at the receiver.

4. Bending Loss and Trench

FMFs can display important bending losses for the higher order modes. In these designs with highly asymmetric cores, this is particularly critical when bending around the *y*-axis (i.e., stretching and compressing the core along its long axis). We numerically studied bending loss of the proposed elliptical core fiber, using the conformal mapping technique [29]. We first calculate the equivalent refractive index profile of the bent fiber from which we estimate the modal loss using COMSOL. We found that bending around an axis parallel to the *y*-axis can lead to the cutoff of the last four guided modes. In order to overcome this limitation, two solutions have been proposed in the literature. Increasing the index step improves bending loss, but requires a smaller core dimension in order to maintain the same number of modes. Another approach is adding a trench with depressed refractive index in the cladding to reduce bending loss [29], [30]. Below we combine these two strategies and propose a highly-elliptical core fiber with trench to reduce bending loss. The addition of a depressed index trench is compatible with industry-standard fiber preform fabrication techniques, such as modified chemical vapor deposition (MCVD), used for elliptical core fibers (see fiber fabrication description in [32]). In contrast, introducing a trench around a rectangular core is a much more challenging proposition.

We first increase n_{core} to 1.455, which corresponds to a core-cladding refractive index difference $\Delta n = 1.1 \times 10^{-2}$ (approximately 7.3% molar fraction of GeO_2 in SiO_2). This relative low Δn is crucial to minimize scattering loss [33]. In addition, we introduce a trench with a depressed index in the cladding, achievable by doping SiO_2 with Fluorine (F), to reach a refractive index value of

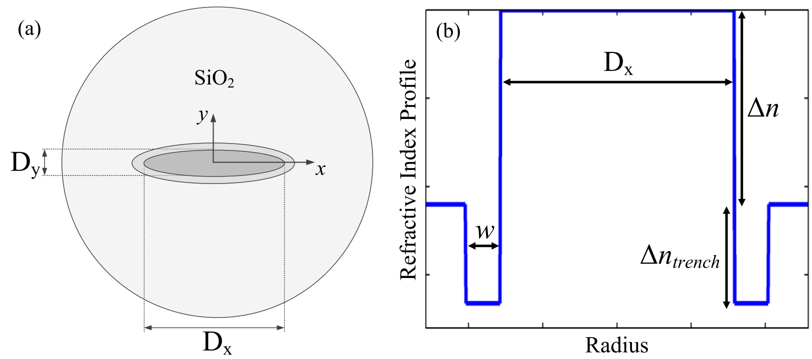

Fig. 3. Geometry and parameter definitions of the highly elliptical core fiber with trench: (a) fiber cross section, and (b) refractive index profile (along the long axis). The inner ellipse fiber core is made of GeO_2-doped silica while the outer one is the depressed index trench made of F-doped silica. D_x and D_y are the core dimensions.

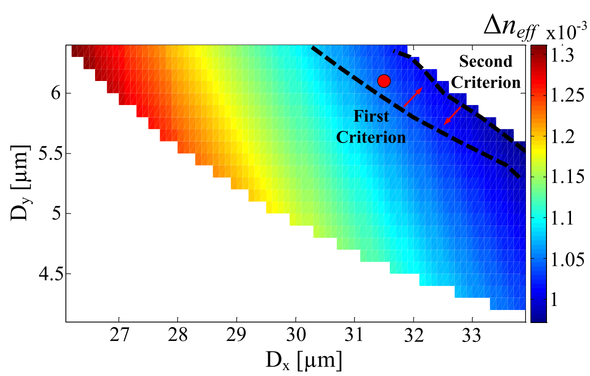

Fig. 4. Minimum Δn_{eff} of the elliptical core fiber as a function of core width and height with $\Delta n = 1.1 \times 10^{-2}$. The colored region is where the fiber supports10 vector modes ($w = 4.6\ \mu$m, $\Delta n_{trench} = -5.6 \times 10^{-3}$). The two black dotted lines represent the two bending loss criteria proposed for SMF [34] for the last guided mode (first criterion) and the first leaky mode (second criterion).

1.4384 at 1550 nm, i.e., $\Delta n_{trench} = -5.6 \times 10^{-3}$ with respect to the silica cladding. Note that the trench parameter range is defined by considering that the maximum achievable value of Δn_{trench} is limited by the fabrication process and is about -5.8×10^{-3}. Figure 3 shows the proposed refractive index profile. With an initial trench width w set to 4.6 μm, we start our investigation by sweeping the width and height of the elliptical core in order to maximize Δn_{eff} and lower bending loss. Figure 4 shows the color map of the minimum Δn_{eff} as a function of the core width (D_x) and height (D_y). The colored region is where the fiber supports 10 vector modes; per the color map, $\Delta n_{eff} > 0.95 \times 10^{-3}$ in this region.

From Fig. 4, we observe vertical color swaths, indicating that the minimum Δn_{eff} depends more strongly on core width, D_x, than core height D_y. The lower left corner on the color map is where the higher order mode (TM_{15}) is cutoff, while the upper right corner is where the next higher order mode (TE_{16}) starts to be guided.

To investigate bending loss, we adopt the two criteria proposed for SMF [34]. The first criterion indicates that the bending loss of the guided mode has to be smaller than 0.0053 dB/m (i.e., 0.1 dB/100 turns) at a bending radius R equal to 30 mm and at the longest wavelength (which is 1565 nm considering the C-band). Fiber dimensions for which this bending loss is achieved at 1565 nm are plotted as the lower dashed black curve. The second criterion is that, the bending loss of the leaky modes should be higher than 1 dB/m at R = 140 mm, and at the shortest wavelength (which is 1530 nm for the C-band). This guarantees that leaky modes will be cutoff and will not

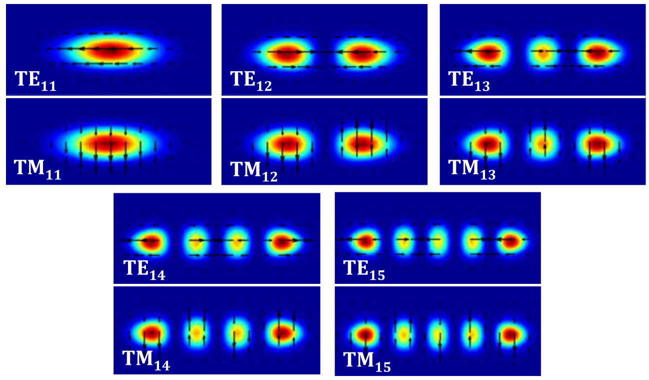

Fig. 5. Simulated mode intensity profiles of the elliptical core fiber with trench. The modes are labeled as TE_{1n} and TM_{1n} depending on their polarization (x and y). Fiber parameters: $D_x = 31.5\ \mu$m, $D_y = 6.1\ \mu$m, $\Delta n = 1.1 \times 10^{-2}$, $w = 4.6\ \mu$m and $\Delta n_{trench} = -5.6 \times 10^{-3}$.

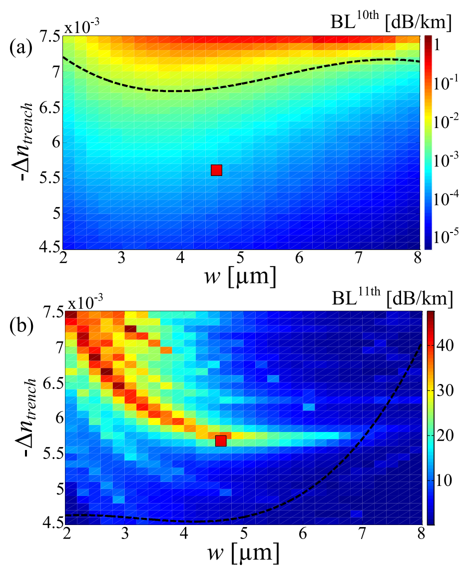

Fig. 6. Calculated bending loss, when bending the fiber around an axis parallel to the y-axis, and when sweeping the trench width and depth for: (a) the last guided mode (i.e., the 10^{th} mode, first criterion), and (b) first leaky mode (i.e., the 11^{th} mode, second criterion). The red square represents the trench parameters of the designed highly elliptical core fiber.

introduce a path for crosstalk. Fiber dimensions for which this bending loss is achieved at 1530 nm are plotted as the upper dashed black curve. The region that meets these two criteria falls between these two dashed black curves, as indicated in Fig. 4. The red dot shows the core dimensions chosen for our fiber design ($D_x = 31.5\ \mu$m and $D_y = 6.1\ \mu$m). Figure 5 shows the calculated mode intensity profiles of the ten vector modes guided by this highly elliptical core fiber with trench, TE_{1n} and TM_{1n} with $n = 1$ to 5. The arrows show the polarization orientations of the electrical fields, x polarization for TE modes and y polarization for TM modes.

Finally we investigate the impact of the trench width, w, and depth, Δn_{trench}, on the bending loss BL. Results of bending loss of the last guided mode (first criterion) are presented in Fig. 6(a) when the fiber is bent around an axis parallel to the y-axis. Bending loss of the last guided mode simulated when bending the fiber around an axis parallel to the x-axis, i.e., stretching and compressing the core along its short axis, are lower and therefore are not shown. The first criterion limits Δn_{trench} since the last guided mode will leak into the cladding under bending if its effective index decreases

TABLE 2
Parameters of the Proposed Highly Elliptical Core Fiber Design

Width (D_x)	Height (D_y)	Δn	w	Δn_{trench}
31.5 μm	6.1 μm	1.1×10^{-2}	4.6 μm	-5.6×10^{-3}

TABLE 3
Mode Properties

Mode	A_{eff} (μm^2)	ER (dB)	δn_{eff} or Δn_{eff}	BL_y (dB/m)	BL_x (dB/m)
TE_{11}	91	51	/	/	/
TM_{11}	90.7	58.1	3.38×10^{-5}	/	/
TE_{12}	103.7	50.2	1.03×10^{-3}	/	/
TM_{12}	103.6	50.5	3.88×10^{-5}	/	/
TE_{13}	107.5	48.6	1.27×10^{-3}	/	/
TM_{13}	107.5	47.1	4.25×10^{-5}	/	/
TE_{14}	109.2	46.8	1.53×10^{-3}	/	/
TM_{14}	109.5	44.7	4.47×10^{-5}	/	/
TE_{15}	111.4	44.7	1.8×10^{-3}	1.2×10^{-5}	2.4×10^{-8}
TM_{15}	111.8	42.6	4.49×10^{-5}	2.1×10^{-5}	4.7×10^{-8}

too much. The refractive index depth of the trench therefore has to be below the dash line in Fig. 6(a). On the other hand, to meet the second criterion (Fig. 6(b)), we need to keep Δn_{trench} high enough to suppress the guidance of the leaky modes in the core; it has to be above the dash line in Fig. 6(b). For the second criterion, the loss when the fiber is bent around an axis parallel to the x-axis presents results similar to the ones shown in Fig. 6(b). In the discussion above, the trench width chosen to calculate Δn_{eff} in Fig. 4 and mode intensity profiles in Fig. 5, falls within the acceptable regions for both criteria; it is marked as a red square in Fig. 6. In Fig. 6(b), although the optimum area is relatively narrow, all points above the black dashed line satisfy the criterion for the minimum loss of the first leaky mode.

5. Highly Elliptical Core Fiber Design

The parameters of the proposed highly elliptical core fiber design are summarized in Table 2. The simulated properties of each mode are presented in Table 3. In addition to modal birefringence (δn_{eff}) and effective index separation to the next mode group (Δn_{eff}), we also list the mode effective area (A_{eff}), calculated polarization extinction ratio (ER) when transmitted through a linear polarizer, and bending loss around an axis parallel to the y-axis (stretching and compressing the core along its long-axis), BL_y, and around an axis parallel to the x-axis (stretching and compressing the core along its short-axis), BL_x. Bending loss are calculated with a radius of 30 mm at 1550 nm. The A_{eff} is between 90 μm^2 and 112 μm^2, compared to typical values of standard single mode fibers

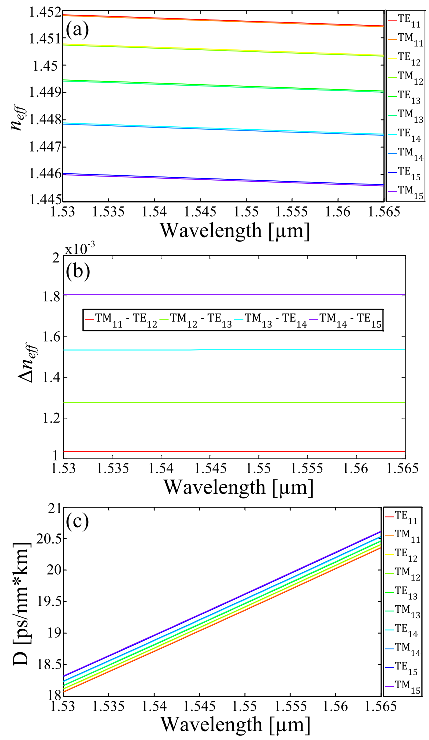

Fig. 7. Properties of the designed highly elliptical core fiber calculated over the C-band: (a) effective index n_{eff}, (b) effective index difference Δn_{eff}, and (c) chromatic dispersion D [ps/nm$*$km].

of 85 μm^2. The extinction ratio of the modes is greater than 42 dB, which indicates that it will be possible to achieve polarization multiplexing by combining orthogonal linearly polarized input signals. BL values are smaller than 5×10^{-11} dB/m unless otherwise indicated in Table 3. As expected, the higher order modes are less sensitive to bending around the *x*-axis.

The mode properties were also calculated over the C-band (from 1530 nm to 1565 nm) by including the wavelength dependent cladding and core refractive indices evaluated with Sellmeier equations [35]. Results are shown in Fig. 7. The Δn_{eff} is found to be quite constant over the C-band with a minimum value between the first and the second spatial mode that is higher than 1×10^{-3}. Chromatic dispersion (D) values are between 18 and 21 ps/nm-km, which is comparable to typical values for SMF, indicating the possibility to use this fiber for short-reach optical interconnects.

6. Scalability

This fiber design has good potential in terms of scalability. As we discussed above, the number of modes can be controlled by changing the size of the long axis of the elliptical core. The dimension of the short axis must be chosen such that only one resonance occurs in this transverse direction, i.e., there is a singly intensity lobe along the *y*-axis. In order to reach a total of 16 channels (8 spatial modes), we considered two different modifications to the design. Firstly, we increase D_x from 31.5 μm up to 48 μm and keep other parameters ($\Delta n = 1.1 \times 10^{-2}$ and $D_y = 6.1$ μm) unchanged. This design leads to the target 8 spatial modes (16 channels) with a minimum Δn_{eff} higher than 0.6×10^{-3}. Alternatively, we can increase the Δn to 2.3×10^{-2} and keep D_x at 31.5 μm. However, in this case, D_y needs to be reduced from 6.1 μm to 4 μm. This second design leads to 8 spatial modes (16 channels) with a minimum Δn_{eff} higher than 1.2×10^{-3}. The latter design also displays a modal birefringence higher than 1×10^{-4} (the average δn_{eff} is 1.6×10^{-4} compared to an average δn_{eff} of 4.3×10^{-5} for the former design). This birefringence could even enable MIMO-less transmission over short distances, i.e., in the range of 1 to 10 km. Figure 8 shows δn_{eff} and Δn_{eff} for

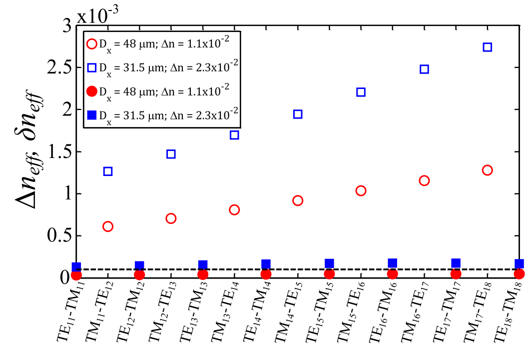

Fig. 8. Δn_{eff} (open markers) and δn_{eff} (filled markers) of two fibers with highly elliptical core designed to support 8 spatial channels, each with two polarizations: the first one has a larger D_x (red markers) and the second one a higher Δn (blue markers).

both designs. In scaling to a higher number of modes, changes in the ellipticity and the refractive index should be traded-off against their negative impact on propagation loss, bending loss and ease of fabrication. A higher D_x causes a higher ellipticity and consequently higher bending loss, while Δn is limited by the fabrication process. In addition, higher order modes present worse ER performance, as indicated in Table 3. However, in the case of 16 modes, the ER is higher than 34 dB, which indicates a good linear polarization properties.

7. Conclusion

Highly asymmetric waveguides present spatial modes that are well separated in terms of effective index. They are ideal candidates for mode-division multiplexing with standard coherent receivers with polarization diversity in order to exploit the full modal basis of the fiber, including the polarization channels. The geometry of the proposed fiber is advantageous when designing silicon photonic multiplexers and demultiplexers, which makes it compatible with low-cost integrated solutions currently being developed for coherent transmission. The proposed highly elliptical core optical fiber is suitable for standard optical fiber fabrication processes, such as modified chemical vapor deposition process (MCVD), facilitating incorporation of an index trench in the cladding to control bending loss. We designed and analyzed, through numerical simulations, a highly elliptical core few-mode fiber supporting five spatial mode groups with twofold polarization degeneracy, yielding a total of ten channels. This highly elliptical core increases Δn_{eff} for lower order modes, compared to the rectangular design, conferring more uniform properties to all channels. It has effective areas and chromatic dispersion compatible with short reach data transmissions. In addition, this approach should be scalable to support more than 16 modes while requiring only 2×2 MIMO equalizer blocks, which would be a significant improvement over current approaches.

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