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A bend-resistant low bending loss and large mode area two-layer core single-mode fiber with gradient refractive index ring and multi-trench

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ABSTRACT

We propose a bend-resistant large mode area single-mode fiber with low bending loss. The fiber consists of three parts, including a two-layer core, a gradient refractive index ring and multi-trench. Performance of the proposed fiber is investigated by using a finite element method at 1550 nm wavelength. Large mode area of 2622 μm^2 at a bend radius of 20 cm can be achieved with the function of the two-layer core and the gradient refractive index ring. The gradient refractive index ring acts as a resonant ring, which also contributes to bend-resistant performance. Bending loss can be reduced to about 0.092 dB/m due to the multi-trench in the cladding, which is also beneficial to improve transmission efficiency. Moreover, the fiber can ensure single-mode operation by exploiting high suppression of the higher order modes. The bending direction has no effect on the performance of the fiber because of the symmetric design.

1. Introduction

Compared with other types of lasers, fiber lasers provide many advantages, especially for the high-power output. High-power fiber lasers can guarantee the intensity of the received signal in a long-distance transmission system without repeaters. So far, nearly 70 years after the initial demonstration of the first fiber laser, continuous-wave fiber lasers have reached 10 kW in the single-mode regime [1,2]. However, the high-power output leads to a problem of nonlinear effects.

In order to break the limit of nonlinear effects, large mode area (LMA) fibers have attracted extensive attention. The power density in the core decreases as the mode area increases, therefore, the threshold of nonlinear effects increases. In addition, LMA fibers can improve optical signal to noise ratio (OSNR) by launching high-power light into fibers [3]. A typical example of LMA fibers is the rod-type fiber which has shown great performance. For example, an Yb-doped rod-type fiber has been proposed in Ref. [4], and the mode field diameter over 100 μm (i.e., the mode area is approximately 7850 μm^2) has been achieved. However, a rod-type fiber has an obvious drawback that it must keep straight, which is disadvantageous for saving space. In order to reduce the device size, one method is to coil the fiber. However, it damages the mode area. At the same time, coiling the fiber also increases the bending loss. As we know, high bending loss reduces efficiency and wastes energy. Moreover, it also reduces the output OSNR for the same distance [3].

To solve the problem mentioned above, researchers try to design a LMA fiber with low bending loss. A modified leakage channel fiber with large mode area and low bending loss has been achieved by introducing low-index rods into the core in Ref. [5]. However, the fiber can only be bent with specific bending orientation angle due to its asymmetric structure. Besides, several other fiber designs have also been proposed to achieve large mode area and low bending loss, for example, photonic crystal fibers [6,7], Bragg fibers [8–10], photonic bandgap fibers [11,12], multi-core fibers [13,14], large-pitch fibers [15,16], multi-trench fibers [17–19], etc.

Single-mode operation also needs to be considered in a fiber design. Generally, higher order modes (HOMs) appear as the size of the core increases [20]. This leads to a phenomenon called mode competition which will deteriorate the beam quality and cause modal instability [21,22]. For a normal straight step-index fiber, the cutoff wavelength can be simply calculated according to the corresponding formula [23]. The single-mode operation can be achieved as long as the fiber is at a wavelength which is longer than the cutoff wavelength. However, for a fiber with more complex refractive index distribution, single-mode operation can be ensured by exploiting high suppression of the HOMs. There are two approaches to judge effective single-mode operation. One is to exploit the power fraction difference between fundamental mode (FM) (we choose the one with lower power fraction between the two

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polarizations) and HOM (we choose the one with the highest power fraction among all the HOMs). Single-mode operation can be ensured when the difference is larger than 30% [24]. The other is to exploit the bending loss of FM (we choose the one with higher bending loss between two polarizations) and HOM (we choose the one with the lowest bending loss among all the HOMs). Generally, the fiber is sufficient for effective single-mode operation as long as the maximum loss of the two polarizations of FM is lower than 0.1 dB/m and the minimum loss of HOMs is higher than 1 dB/m [17]. In this paper, the second method is used.

In this paper, we propose a two-layer core fiber with multi-trench and a gradient refractive index ring in the cladding. The fiber offers low bending loss owing to the low refractive index trenches in the cladding. With the modulation of a gradient refractive index ring and a two-layer core, the fiber can achieve large mode area of 2622 μm^2 under a bend radius of 20 cm at a wavelength of 1550 nm. Compared with a step-index ring [25], the gradient refractive index ring can offer larger mode area, moreover, it also makes contribution to bend-resistant performance. The proposed fiber can ensure good beam quality by realizing effective single-mode operation. Owing to its symmetric structure, the fiber can be bent at any angle without affecting its performance.

2. The structure of the proposed fiber

Fig. 1(a) shows the 2D cross section of the proposed fiber. Fig. 1(b) shows the refractive index profile of the proposed fiber. The light blue region represents the inner core and the red region represents the second layer core. The yellow region represents the gradient refractive index ring. The dark blue region represents multi-trench in the cladding. And the grey region represents the remaining parts of the fiber. The refractive index values of the light blue, red, grey and dark blue regions are $n_0 = 1.44$, $n_1 = 1.4399$, $n_2 = 1.4395$ and $n_3 = 1.439$, respectively. For the yellow region, the refractive index profile is gradient, and the highest refractive index is the same as the inner core, which is set as $n_0 = 1.44$.

It can be seen from Fig. 1(b) that the proposed fiber consists of three parts: a two-layer core, a gradient refractive index ring and multi-trench. Due to multi-trench with lower refractive index, the bending loss obviously decreases [26], which contributes to single-mode operation and higher transmission efficiency. The thicknesses of the two trenches are both d_1 and the distance between the two trenches is t_1. The two-layer core is introduced to adjust the refractive index difference between the core and the cladding, which is of great benefit to large mode area. The radiuses of the two layers in the core are r_0 and r_1, respectively. The gradient refractive index ring acts as a resonant ring to achieve large mode area. The thickness is d and its distance from the core is t. In fact, the fiber with a step-index resonant ring has been proposed before [25], however, the gradient refractive index ring can achieve better performance which includes larger mode area and better bend-resistant ability. The authenticity will be given below according to simulations. The highest refractive index of the gradient refractive index ring is the same as the inner core and the refractive index profile follows the following formulas:

$$n = n_0\left[1-2\Delta\left(\frac{|r|-d_0}{d/2}\right)^{\alpha}\right]^{1/2} \tag{1}$$

$$d_0 = r_1 + t + \frac{d}{2} \tag{2}$$

$$\Delta = \frac{n_0^2-n_2^2}{2n_0^2} \tag{3}$$

where n_0 is the highest refractive index of the gradient refractive index ring, n_2 is the lowest refractive index of the gradient refractive index ring, r is the radius of the position, Δ is the relative refractive index difference, α is the refractive index distribution constant which is set as 2 in this paper.

The distortion of the refractive index occurs when the fiber is bent. Hence, the refractive index profile can be expressed with an equivalent formula [24]:

$$n^2 = n_s^2\left(1 + 2\frac{r}{\rho R}\cos\theta\right) \tag{4}$$

where n_s is the refractive index of the straight fiber, r is the radius of the position, θ is the azimuthal angle, ρ is the stress factor, R is the bend radius which is set as 20 cm in the paper.

Finite element method (FEM) is chosen to demonstrate the high performance of our proposed fiber. A perfectly matched layer (PML) is added outside the cladding, which is used to calculate bending loss accurately. As the PML acts as an almost reflectionless absorber, it works quite well to absorb the leaky wave propagating towards to the boundaries [27,28]. As mentioned in the previous section, single-mode operation is ensured by judging the bending loss of FM and HOMs, therefore, calculating the bending loss accurately is important. The simulations of the paper are performed at a wavelength of 1550 nm.

3. Numerical simulations

To investigate the performance of the proposed fiber with a two-layer core, a gradient refractive index ring and multi-trench, the fiber structure in Fig. 1 is simulated by using FEM. The relevant parameters are set as $r_0 = 30\,\mu m$, $r_1 = 35\,\mu m$, $r_2 = 200\,\mu m$, $R = 20$ cm (R is the bend radius), $t_1 = \{16–18\,\mu m\}$, $d_1 = \{10–12\,\mu m\}$, $t = \{17–19\,\mu m\}$, $d = \{12–13\,\mu m\}$, respectively.

First, the effect of the multi-trench is investigated by varying the relevant parameters t_1 and d_1. Meanwhile, the parameters t and d are

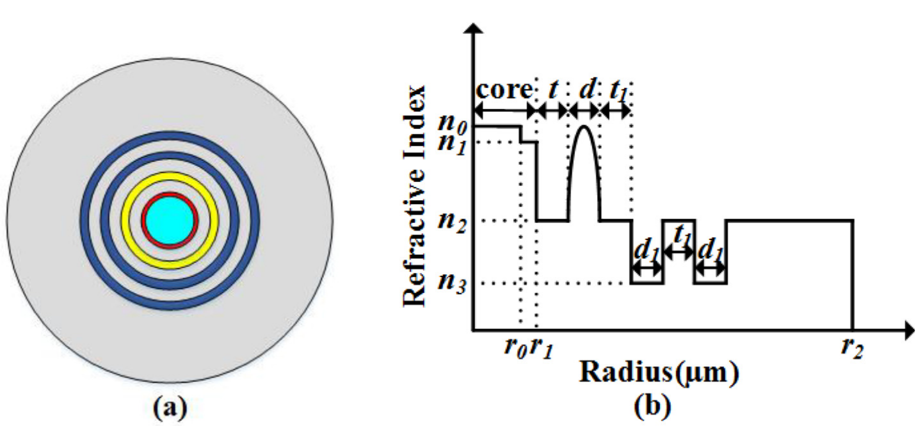

Fig. 1. (a) 2D cross section and (b) refractive index profile of the two-layer core fiber with multi-trench and a gradient refractive index ring in the cladding.