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Very large mode area optical fiber with complex ring cores

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ABSTRACT

A novel kind of single-mode large-mode-area optical fiber is presented in this paper. The proposed fiber core is composed of high-index central rod and the surrounding multilayer rings. The mode characteristics are discussed considering the fiber structure parameters. The calculation results show that the proposed fiber possesses extreme large mode area of 2975 μm^2 with single mode operation at the wavelength of 1.08 μm. Even larger mode area of the complex ring core fiber with single mode output can be achieved by coiling the fiber, due to the significant difference of bending loss between the fundamental mode and the higher-order transverse modes. Such fibers are expected to find applications in the field of fiber lasers and amplifiers.

1. Introduction

Single mode optical fibers with large mode area (LMA) have attracted much attention concerning applications in the field of fiber amplifiers, fiber lasers and high power beam delivery systems [1]. High power laser in the small core of a conventional single-mode fiber gives rise to unwanted nonlinear effects. It indeed constitutes the main performance limitation of fiber lasers and amplifiers. The realization of LMA in a conventional single mode step-index optical fiber requires a low numerical aperture (NA) to increase core diameter. It is generally difficult to fabricate a step index fiber with NA lower than ~0.06. The core diameter of conventional single mode fiber is limited to approximately 15 μm for the 1 μm wavelength region [2]. The fiber becomes multi-mode by a further enlargement of the core diameter. However, the significant difference of bending loss between the fundamental mode and the higher-order transverse modes especially at a low NA can be used to force such a multimode fiber to single-mode operation [3], due to the fact that the higher order modes can be eliminated after a moderate propagation distance. This technique works well up to core diameters in the range of 30 μm, robust single-mode behavior in even larger cores is nearly impossible.

The invention of microstructured optical fibers, especially photonic crystal fibers (PCF) has led to the appearance of various kinds of novel LMA optical fibers. A multicore fiber consisting of 19 hexagonally arranged cores has been explored and it was measured that an effective mode area was of 465 μm^2 for single-mode operation [4]. Napierała et al. designed a PCF with double lattice constant structure, and it enables single mode operation with a mode area that reaches 1454 μm^2 [5]. Limpert et al. fabricated an extended single mode ytterbium-doped PCF with mode area of ~2000 μm^2 [6]. A power of 320 W has been extracted with this fiber in a continuous-wave experiment. The mode-field-area of fundamental mode is as large as 2300 μm^2 in a single polarization Yb-doped rod-type PCF [7]. A novel flexible PCF was designed with mode-field-area exceeding 2500 μm^2 [8]. A multi-layer cladding large-mode-area optical fiber has also been proposed [9]. The cladding is formed by alternate high and low-index regions specially designed to strip-off high order modes. With the proposed design a fiber with 30 μm core diameter (i.e. mode area ~ 2800 μm^2) and NA ~ 0.16 can exhibit single-mode operation at 1.55 μm wavelength.

In this paper, we present a novel type of all-solid complex ring core LMA optical fiber. The complex ring core is composed of high index Yb-doped multilayer rings separated by low index claddings. The proposed fiber preform, relative to PCF preform with air-hole cladding, is easy to be fabricated by just alternating deposition of the high and low index layers by using modified chemical vapor deposition (MCVD) method, and the difficulties in the drawing process for the fiber is also reduced comparing with that of PCF. The calculation results show that the proposed fiber possesses extreme large mode area of 2975 μm^2 with single mode operation at the wavelength of 1.08 μm, and the even larger mode area of the fiber with single mode output can be achieved by bending the fiber with proper bending radius.

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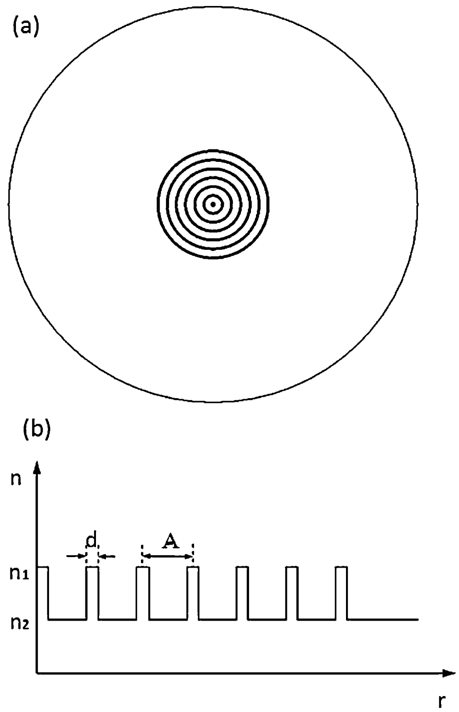

Fig. 1. (a) Cross section of the optical fiber with 6 layers ring cores. The black zones represent the high refractive Yb-doped ring cores and the white zones denote the low refractive pure silica cladding. (b) The index distribution profile of the fiber along x axis.

2. Numerical simulation

The cross section of the proposed fiber is shown in Fig. 1(a). The core is composed of a high index rod in the center and the surrounding high index multilayer rings embedded in the background of pure silica. The index profile of the fiber along x axis is shown in Fig. 1(b). In the fiber model, the radius of central rod and the width of high index rings are defined as d. The central distance between two adjacent high index rings is Λ. The number of high index rings is set as 6 in this paper, which is considered typical. The index of the ring core is n_1, while the index of background cladding is n_2, and assumed to be 1.45. The index contrast between core and cladding is defined as $\Delta n = n_1 - n_2$. The diameter of the outermost cladding of the fiber is 400 μm.

We have analyzed the fiber by calculating the effective index of the core n_{eff}, V parameter and mode profile using finite element method (FEM) [10]. FEM can present an accurate solution of the Maxwell equations for fibers with arbitrary index distribution [11]. A circular perfectly matched layer (PML) [12] in association with a perfect electric conductor was used as boundary condition. The V parameter is defined as

$$V = \frac{2\pi a}{\lambda}\sqrt{n_{eff}^2 - n_2^2} \tag{1}$$

where λ is the operation wavelength and $a = 6\Lambda$ is the radius of the complex ring core. The effective mode field area is defined as [4]

$$A_{eff} = \frac{\left(\iint_S (EE^*)^2 dx\, dy\right)^2}{\iint_S (EE^*)^4 dx\, dy} \tag{2}$$

where E represents the electric field, E^* the complex conjugate. S is the cross section area of the fiber.

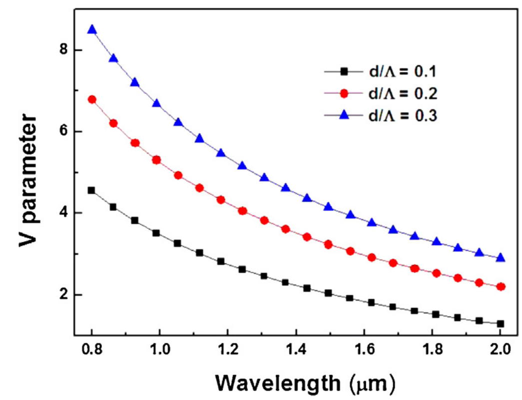

Fig. 2. V parameter as a function of wavelength with different d/Λ, $\Delta n = 0.001$.

3. Discussions

V parameter is an important quantity which is used to characterize the propagation mode numbers in an optical fiber. The fibers with small V value while maintaining large effective mode area are desired for high power fiber lasers or amplifiers with high beam quality. Single mode operation can be realized as long as the V value is lower than 2.405, according to optical fiber theory. We investigated the dependence of V parameter on wavelength with different d/Λ, Λ = 6 μm, as shown in Fig. 2. V value decreases with wavelength increasing and with d/Λ decreasing at the whole wavelength range from 0.8 to 2.0 μm. The effective index difference $\Delta n_{eff} = n_{eff} - n_2$ between core and cladding for the proposed fiber, on the order of 10^{-4}, decreases with wavelength increasing. It is easier to realize single mode operation with small Δn_{eff} at long wavelength. The decrease of d/Λ with fixed Λ also leads to the decrease of Δn_{eff}. Therefore to decrease the width of high index rings is necessary to realize single mode operation for a given wavelength. The gain fiber used in the fiber lasers we fabricated is ytterbium-doped and the laser wavelength is generally 1.08 μm. So the wavelength of the signal light transmitted in the proposed fiber is fixed at 1.08 μm in the following simulation.

V parameter is related closely to the structure parameters of the complex ring core fiber. Fig. 3 shows V parameter as a function of Λ with different d/Λ and Δn. It can be found that V value increases almost linearly with Λ increasing. It means that Λ, i.e. the distance between two adjacent high index rings, must be small to keep small V value, though large Λ can lead to large mode area of the fiber. It also shows in Fig. 3(a) that decreasing d/Λ can effectively lower V value. Fig. 3(b) shows V parameter with different Δn. Apparently, larger Δn is generally not suitable for the realization of single-mode guidance with large mode area.

Fig. 4 shows the dependence of effective mode field area A_{eff} of fundamental mode on structure parameters of the complex ring core fiber. A_{eff} increases monotonously with Λ increasing. So large Λ is needed to obtain Large A_{eff}, which is desired for high power fiber lasers. However, the fiber become multimode guided when Λ is larger than a specific value as discussed above. The maximum A_{eff} of the single mode guided fiber with complex ring core have been denoted by hollow pentagrams in Fig. 4. In particular, A_{eff} of the fiber with Δn = 0.001, d/Λ = 0.1, and Λ = 4.9 μm is 2975 μm^2. It can be found from Fig. 4(b) that A_{eff} decreases with Δn increasing, owing to the fact that more of field power will concentrate to the high index ring cores with increasing high index contrast between core and background. The small Δn leads to the extending of the mode field to the low index background, which results in the increase of the mode area. Therefore, the small d/Λ and Δn can help increase the mode areas.