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Design and analysis of novel multilayer-core fiber with large mode area and low bending loss

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ABSTRACT

A novel multilayer-core intrinsically single-mode large-mode-area fiber is proposed in this paper. The multilayer structure in the core which is constituted of alternating low- and high-refractive index rings could achieve a very low equivalent core-cladding refractive index difference. The single-mode large mode area of 100–12,000 μm^2 could be achieved in the fiber. The effective area A_{eff} can be further enlarged by increasing the parameters of low-refractive index rings or the number of layers. Furthermore, the bending property could be improved by 1–2 orders of magnitude in this multilayer-core structure when the outermost layer is depressed-index ring. We have experimentally verified the proposed fiber structure that follows the target of large A_{eff} along with ultra low bending loss at 1.55 μm. These characteristics of multilayer-core fiber suggest that it can be used in large-mode-area high-capacity transmission, or high-power optical fiber laser and amplifier in the optical communications.

1. Introduction

Single-mode large-mode-area fibers (LMAF) are of great interest for high-power transportation due to their high threshold of nonlinearities, and for their high energy storage capacity in applications such as fiber laser systems and power amplifiers for telecommunications. For a further increase of the output power, a current challenge lies in the scaling of the effective area (A_{eff}) in the fiber (in order to ensure non-linear effects mitigation), while maintaining a single-mode output (in order to ensure a good output beam quality).

Several fiber structures have been proposed to achieve single-mode operation and large fundamental mode A_{eff}, as low-NA step-index fibers [1], Bragg fibers [2], Photonic Crystal Fibers (PCF) [3], and Leakage Channel Fibers (LCF) [4–6]. The main drawbacks of all these approaches are their difficult fabrication, due to the requirement of stringent control of low-NA (this is even more difficult when a high level of rare earth ions are added in the core, causing further index elevation), stack and draw technique, and a frequent hexagonal shape for the output beam. Furthermore, it is a trade-off between the A_{eff} and bending loss. The scaling of the A_{eff} in such fibers is limited due to detrimental bending effects [7].

In this paper, we proposed a novel multilayer-core intrinsically single-mode large-mode-area fiber. The multilayer structure in the core which is constituted of alternating low- and high-refractive index rings could achieve a very low equivalent average core-cladding refractive index difference. The single-mode large mode area of 100–12,000 μm^2 could be achieved in the fiber. The A_{eff} can be further enlarged by increasing the parameters of low-refractive index rings or the number of layers. Furthermore, the bending property could be improved in this multilayer-core structure when the outermost layer is depressed-refractive index ring. The bending loss could decrease by 1–2 orders of magnitude compared with the step-index optical fibers (SIF) with the same A_{eff}. To experimentally validate the proposed fiber, we have measured the fabricated multilayer-core fibers (MLCF). It has been verified experimentally that the MLCF structure can enlarge the effective area A_{eff} while maintaining lower bending loss.

2. Design and analysis

2.1. MLCF presentation

There are two approaches to achieving single-mode operation in step-index (SI) LMAF [8]. The first one is to design a multimode SI-LMAF with a few modes. For the multimode SI-LMAF, the fiber intrinsically supports several modes. Effective single-mode operation can be achieved by stripping higher order modes (HOMs), for instance, LCF based on leaky HOMs [6]. One of the typical designs is Bragg fiber in which confinement of light occurs due to the photonic bandgap created by the periodic layers [9]. It is well known that Bragg fiber is a leaky optical waveguide [10], and it is an essential multimode fiber in which effective single-mode

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operation is achieved by inducing a large differential loss to its HOMs. Such fiber should be fabricated through the extrusion process [11]. However, it is difficult to satisfy the stringent demands of the refractive index and layer thickness.

Another approach is to design an intrinsically single-mode SI-LMAF with the cutoff wavelengths of HOMs below the operating wavelength. The fiber NA cannot be arbitrarily low as it is limited by the conventional manufacturing process. A fiber core NA lower than 0.05 is generally difficult to achieve [8]. The upper limit of effective area that can achieve SM operation is around 370 μm^2 taking into account the feasibility of NA that can be achieved with today's technology.

A way to break this limit value of A_{eff} is to use a microstructured core (inhomogeneous core) where the mean refractive index leads to a lower index difference and the homogeneous parts exhibit an index difference higher than the limit value. In this paper, the proposed multilayer-core fiber behaves in this way. The multilayer core which is made of alternating low- and high-refractive index layers could achieve a very low equivalent average refractive index. The actually low NA (lower than 0.05) is much easier to achieve compared with that of single-mode SI-LMAF in the aspect of manufacturing processes. It is worth noting that the proposed fiber structure is different from that of Bragg fiber. This fiber is an intrinsically single-mode LMAF which belongs to the second approach. The proposed periodic layers constitute the fiber core in which the fundamental mode distributed, whereas the periodic layers constitute the fiber cladding in Bragg fiber. The guide-light mechanism is very different for the two fiber types. The fundamental mode in the proposed fiber is guided mode, whereas in Bragg fiber the fundamental mode lies well within the photonic bandgap.

2.2. *Large-mode-area property*

A cross section structure schematic of the multilayer-core single-mode large-mode-area fiber is shown in Fig. 1. The fiber core consists of alternating low- and high-refractive index rings. Gray and white colours represent high and low-refractive index regions, respectively. There are two types of fiber structures formed by the periodic core. The structure with center layer formed by high-index rings is called center-high-index MLCF (C-H MLCF). The structure with center layer formed by low-index rings is called center-low-index MLCF (C-L MLCF). The high index could be raised by the presence of erbium and aluminum. Doping with fluorine creates the depressed index regions. The cladding is pure silica. The cladding diameter is $d_{clad} = 125$ μm, and the refractive index is set as $n_{clad} = 1.444$. The structural parameters consist of the thickness of the high-index rings a, the thickness of the low-index rings d, the refractive index difference between the high-index rings and the cladding $\Delta_1 = n_1 - n_{clad}$, the refractive index difference between the cladding and the low-index rings $\Delta_2 = n_{clad} - n_2$, and the number of layers n.

The fundamental modes field distributions of C-H MLCF and C-L MLCF are shown in Fig. 2. The operating wavelength is fixed at 1.55 μm. In order to ensure single-mode operation at 1.55 μm, the cutoff wavelength λ_C should be fixed less than 1.55 μm. As per G652 recommendations, the cable cutoff wavelength should be less than 1.26 μm. Here the cutoff wavelength is fixed at $\lambda_C = 1.26$ μm. As shown in the figure, the fundamental mode field is distributed in the whole periodic layers which constitute the fiber core. It is different from that of Bragg fiber in which the fundamental mode field is not distributed in the periodic layers which constitute the cladding. Due to the multilayer-core structures the mode field distribution of fundamental modes in both proposed types of fiber structures is not approximately Gaussian distribution. Consequently, the modes effective area A_{eff} is calculated from Petermann I definition

$$A_{eff} = \frac{2\pi \int_0^\infty \mathbf{E}^2 r^3 dr}{\int_0^\infty \mathbf{E}^2 r dr} = \frac{2\pi \oiint_\Omega \mathbf{E}^2 (x^2 + y^2) dxdy}{\iint_\Omega \mathbf{E}^2 dxdy} \tag{1}$$

here $\boldsymbol{E}$ is the mode electric field.

The effective index n_{eff} and the mode effective area A_{eff} of fundamental mode in the fiber are investigated in this paper. The effective index n_{eff} and effective area A_{eff} at various structural parameters for C-H MLCF and C-L MLCF is shown in Fig. 3. The thickness of the high-index rings a is determined such that the cutoff wavelength is to be 1.26 μm. Other structural parameters are fixed as $d = 1.5$ μm, $\Delta_2 = 0.004$; $d = 1.5$ μm, $\Delta_1 = 0.001$; $\Delta_1 = 0.0025$, $\Delta_2 = 0.004$; $d = 1.5$ μm, $\Delta_1 = 0.001$, $\Delta_2 = 0.004$ for Fig. 3(a)–(d), respectively. Because the detailed results of outermost layer being high-index ring are quantitatively different from that of outermost layer being low-index ring, the two cases should be separately discussed. Further investigation shows that the variation tendencies of them are similar. For simplicity, here we only discuss the case of outermost layer being high-index ring. In order to ensure the outermost layer being high-index ring, the number of layers n has to be odd number for C-H MLCF and even number for C-L MLCF. Here n is assumed to be $n = 5$ and $n = 6$ for C-H MLCF and C-L MLCF, respectively.

As shown in Fig. 3(a), as the refractive index difference Δ_1 increases, the refractive index of the core increases. Consequently,

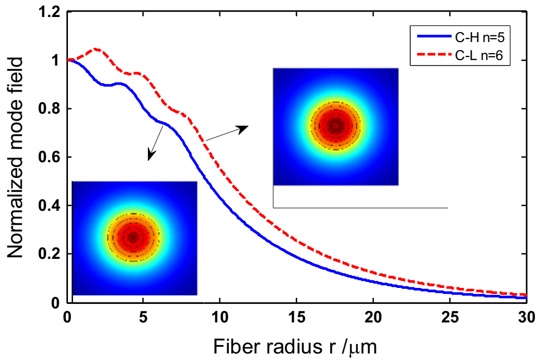

Fig. 2. Normalized fundamental mode field distribution of C-H MLCF and C-L MLCF.

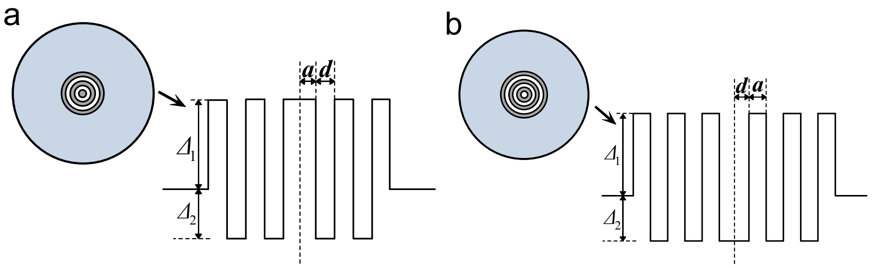

Fig. 1. Cross section schematic of MLCF structure. (a) C-H MLCF, (b) C-L MLCF.