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Design and analysis of a modified segmented cladding fiber with large mode area

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ABSTRACT

This paper proposes a novel segmented cladding fiber structure for large mode area properties. In this structure a thin ring is placed between the high index core and nonuniform cladding. It is called Single-Ring Segmented-Cladding Fiber (SR-SCF). The novel fiber offers the possibility of single-mode(SM) operation from 1 μm to 1.7 μm with a large core diameter. With illustrations, the fiber has a better SM operation than segmented-cladding fiber (SCF) is demonstrated. A large effective area of 1000 μm^2 is achieved. The SM operation with very high suppression of the higher order modes can arise by 76%. Moreover, mode spacing between the adjacent modes (LP_{01} and LP_{11}) is also improved significantly. Besides, the bending property is analyzed. It is found that the fiber is insensitive to bending angle ranging from −180° to 180° at bending radius of 30 cm. The proposed fiber will play an important role in developing high power fiber laser, fiber amplifier and high power delivery application.

1. Introduction

The fiber amplifiers/lasers have developed rapidly in terms of brightness, beam quality, heat dissipation, efficiency and operating costs [1–3]. However, for a further increase of the output power, the fiber nonlinear effect comes to be the most important challenge. To mitigate the nonlinear effect, the most effective way is to increase the mode area by enlarging the core diameter. But the number of transverse modes often increases with core diameter, and the beam quality will deteriorate consequently. Hence, it is important for high power fiber lasers and amplifiers to have a fiber structure which achieves large mode area (LMA) and single-mode(SM) operation simultaneously.

Recently, a lot of research efforts have been devoted to fiber lasers, which aims at achieving with both requirements. Such as Double Clad Fibers [4], Chirally-Coupled-Core (CCC) Fibers [5], Multi Core optical fibers [6], Photonic Bandgap Fibers [7,8], Photonic Crystal Fibers (PCF) [9–11], Leakage Channel Fibers (LCF) [12], Multi-Layer Cladding Fiber [13], Segmented Cladding Fibers (SCF) [14,15], and Gain-Guided and Index Anti-Guided (GG+IAG) optical fibers [16]. However, the application limits of these fibers are the complex and expensive fabrication and detrimental bending effects.

SCF consists of a large core of high refractive index and a cladding with regions of high and low refractive index alternating angularly. SCF is a fiber which adjusts leakage structure to a very short length. It is needed to attenuate the higher-order modes by designing reasonable parameters. Thus, large mode field and SM operation are obtained. SM operation can be achieved with high suppression of higher order modes. SCF not only has large mode field area but also better beam quality. It breaks the limitation of the characteristics of traditional large mode area fiber whose output quality is poor [14,15]. As the radius of SCF is determined, the effective area is limited and the ratio between LP_{11} and LP_{01} is hard to rise. SCFs can be fabricated in silica-based glass by stack-and-draw technique and bicomponent spinning [17,18]. Moreover, SCFs designed and fabricated for the mid-IR with a large core is also reported [19–22]. The fiber core radius can achieve as large as 70 μm [19]. The fibers can also be extruded from silver-halide crystals by using the 'rod in tube' method [20]. They are highly transparent in the middle infrared [21,22]. SCFs have great potential as low-loss single-mode fibers for the mid-IR.

In this work, a novel optical fiber design that consists of a large core, a thin inner cladding and an outer cladding is presented. The outer cladding is formed by alternating regions of high and low refractive indices in an azimuthal direction. We call it Single-Ring Segmented-Cladding Fiber (SR-SCF). The single ring is flexible whose refractive index and thickness can be adjusted to achieve multiple purposes. The SR-SCF behaves like a SCF or a photonic-crystal fiber.

A detailed theoretical analysis of the SR-SCF is presented. To

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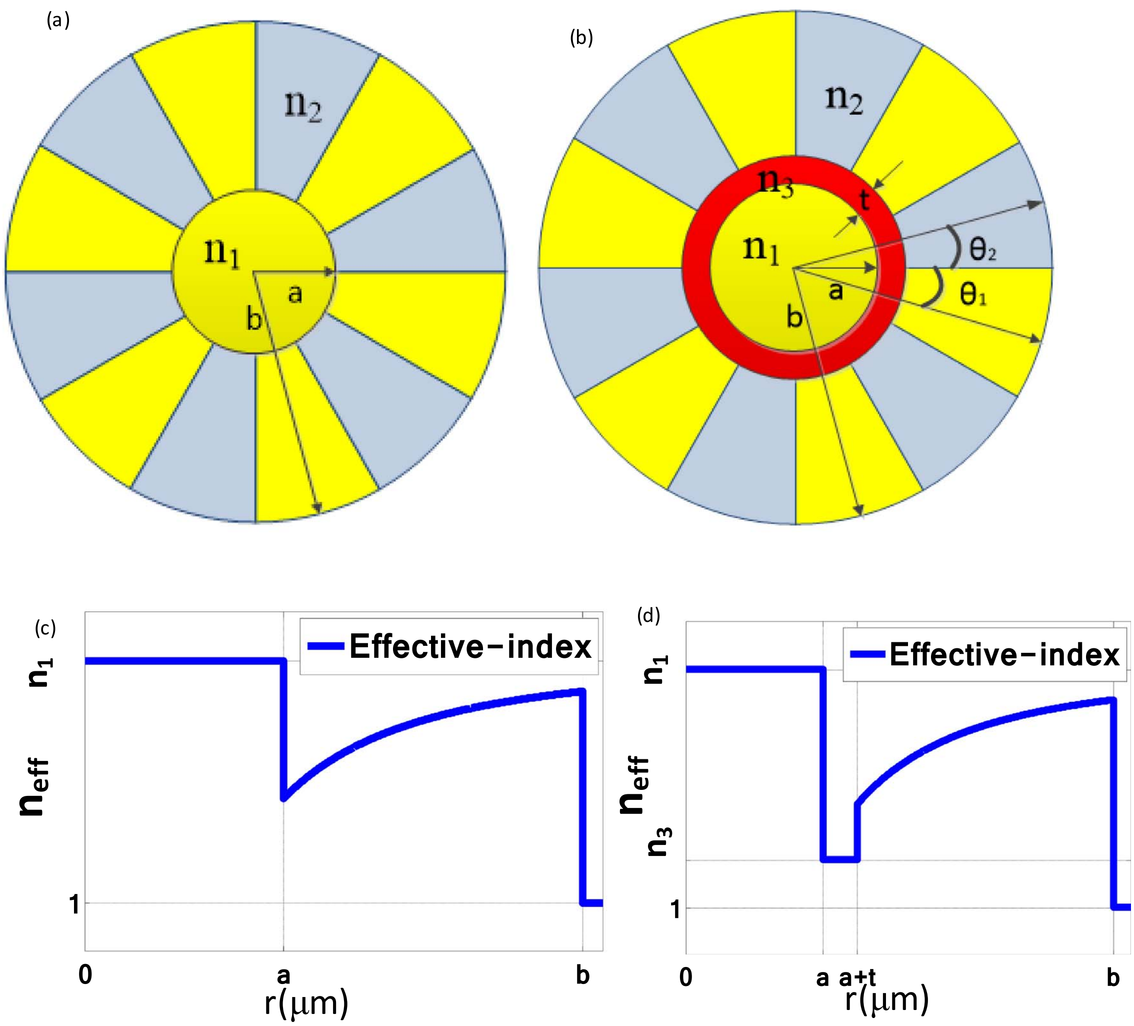

Fig. 1. Schematic cross-section of (a) SCF structure and (b) SR-SCF structure. Effective index profile of (c) SCF and (d) SR-SCF.

calculate the leakage losses of the modes of SR-SCF, the finite element method is applied. Because the performance of the fiber is characterized by its leakage losses, how the leakage losses depend on the physical parameters of the fiber is studied in detail. The results reveal some general principles for the design of fiber for different applications. SR-SCF and traditional SCF are researched at the same parameters to study the influence of single ring. The SR-SCF can offer single-mode operation over 1–1.7 μm with a large core area. The mode area can achieve to 1000 μm^2, while the ratio between HOMs and FM is larger than SCF by 76%. The mode spacing of SR-SCFs and the propagation characteristics in different single ring parameter are also to be discussed later.

2. Single Ring Segmented Cladding Fiber presentation

The transverse cross section of a SCF and SR-SCF is shown in Fig. 1. The fiber comprises a uniform core region ($0<r<a$) of refractive index n_1, a thin single ring ($a<r<a+t$) of refractive index n_3 and a segmented cladding region ($a+t<r<b$). The cladding consists of segments of high-index (n_1) medium of angular width $2\theta_1$ and low-index (n_2) medium of angular width $2\theta_2$ that alternate periodically and angularly. The index difference among three media is characterized by $\Delta n=n_1-n_3$, $\Delta n_2=n_1-n_2$.

Fig. 1(a) and (b) present the notations used in this paper: a is the core radius, t is the thickness of the single ring, b is the fiber radius, n_1 is the refractive index of the core and high refractive index part in outer cladding, n_2 is the low refractive index part in outer cladding, n_3 is the refractive index of single ring, $2\theta_1$ is high-index (n_1) medium of angular width, $2\theta_2$ is low-index (n_2) medium of angular width. The period and duty cycle of the segmentation are given by $\Lambda=2\theta_1+2\theta_2$, and $\gamma=\theta_2/(\theta_1+\theta_2)$. N is the number of the respective segment. The traditional SCF is a special condition of SR-SCF in the case of $t=0$.

The effective-index profile of SCF can obtained from Radial-Effective-Index Method (REIM) [19]. With REIM, we assume that the relative difference Δn is small ($\Delta n \ll 1$). Thus, the transverse component of the electric field satisfies the scalar-wave equation. Expressed in the cylindrical coordinates, the equation can be written as:

$$r^2\frac{\partial^2\phi}{\partial r^2}+r\frac{d\phi}{dr}+\frac{\partial^2\phi}{\partial\theta^2}+k_0{}^2r^2[n^2(r,\theta)-n_{eff}^2]=0 \quad (1)$$

Where φ is the relevant electric or magnetic field, $k_0=2\pi/\lambda$ is the free-space wavenumber, λ is the wavelength, $n(r,\theta)$ is the refractive-index distribution, n_{eff} is the mode index, and r is the radial coordinate. The mode field can be expressed in the following form:

$$\phi(r,\theta)=R(r)\Theta(r,\theta) \quad (2)$$

The field in the fiber is separated into the radial part $R(r)$ and the azimuthal part $\Theta(r,\theta)$. By assuming that $\Theta(r,\theta)$ varies slowly with r as compared with $R(r)$, the problem is reduced to solving following two ordinary differential equations, which are satisfied by $R(r)$ and $\Theta(r,\theta)$, respectively, using the appropriate boundary conditions: