Optics Communications 284 (2011) 5688–5691

Contents lists available at SciVerse ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Design and analysis of multi-ring microstructured-core optical fibers

Ming-Yang Chen *, Yong-Kang Zhang

Department of Optical Engineering, School of Mechanical Engineering, Jiangsu University, Zhenjiang 212013, Jiangsu Province, China

ARTICLE INFO

Article history:
Received 15 September 2010
Received in revised form 28 February 2011
Accepted 24 August 2011
Available online 10 September 2011

Keywords:
Single mode
Large mode area
Finite-element method

ABSTRACT

A novel design of single-mode large-mode-area optical fiber is presented. The core is composed of alternate high and low-index regions to form an effectively low-index contrast between the core and the cladding. The proposed fiber is investigated by the finite-element method with anisotropic perfect matched layer boundary conditions. In addition, the bending losses of the fibers are calculated and compared with those of the step-index optical fibers. In particular, numerical simulations demonstrate that single-mode operation can be achieved in one such fiber with mode area larger than 600 μm^2 at the wavelength of 1.55 μm and bending loss lower than 0.02 dB/m for bending radius greater than 20 cm.

1. Introduction

Transmission of high power light in the small core of a conventional single-mode fiber leads to high power densities and gives rise to significant unwanted nonlinear effects. Nonlinear effects in a fiber can distort the pulses at high bit rate and can produce crosstalk among the closely spaced wavelengths. The realization of large-mode area in a conventional optical fiber requires a low-index contrast between the core and the cladding so that single-mode operation can be maintained. However, an step-index optical fiber with numerical aperture (NA) lower than 0.05 is generally difficult to achieve in conventional manufacturing processes [1]. The invention of microstructured optical fibers has lead to the appearance of various kinds of novel large-mode optical fibers [2–10]. Single-transverse-mode rod-type photonic crystal fiber with mode-field-area as large as 2300 μm^2 have been reported [8]. The single-mode large-mode-area optical fibres can be realized by the enhanced differential loss between the fundamental mode and the high-order modes so that the high-order modes can be eliminated after a moderate propagation distance [2,3,5]. Fundamental-mode operation is possible in all-glass leakage channel fibers with core diameter beyond 100 μm. A multilayer cladding large-mode-area optical fiber has also been proposed [4]. The cladding is formed by alternate high and low-index regions specially designed to strip-off high-order modes. Poli et al. proposed the suppression of first higher-order mode in rod-type photonic crystal fibers by the selected doping in the core of the fiber [6]. Absolutely single-mode operation is possible in large-mode area microstructured-core optical fibers [11–14]. In particular, the porous fibers, a kind of optical fiber containing an array of sub-wavelength holes separated by sub-wavelength material veins, has been proposed for low-loss guiding of terahertz radiation. Total fiber loss of less than 10 dB/m, bending radii as tight as 3 cm, and fiber bandwidth of ~1 THz is predicted for the porous fibers with sub-wavelength holes [14].

In this article, we will propose a novel kind of large-mode-area optical fibers, the core of which is composed of alternate high and low-index regions. The multi-ring configuration in the core forms an effectively low-index core. The preform of the proposed multi-ring optical fiber (MROF) can be formed by using the conventional manufacturing processes. Numerical investigations single-mode operation in the fibers can be realized as long as they are worked below the cutoff frequency of higher-order modes.

2. Numerical simulation

The MROF we proposed is illustrated in Fig. 1. The fiber is characterized by the radius of the inner core r_i, the total number of low and high-index layers N, the width of the low-index layer d_l, the width of the high-index layer d_h, the refractive index of the low-index layer n_l, and the refractive index of the high-index layer n_h. The refractive index of the inner core is set as $n_i = n_h$ and the refractive index of the cladding is set as $n_b = n_l$. We also define the period of the layers as $\Lambda = d_l + d_h$. The operating wavelength is fixed at $\lambda = 1.55$ μm. The index contrast between the high-index layer and the low-index layer is defined as $\Delta = (n_h - n_l)/n_l$. We also define structural ratio η as $\eta = d_l/d_h$. The index contrast is set to be$\Delta = 0.001$, which corresponding to an NA of 0.065 for a SIF.

We solve the modes of the proposed fibers by a full vectorial finite-element method with anisotropic perfect matched layer boundary conditions [15–17]. The confinement losses are analyzed through the calculation of the complex effective indices of the fibers. The relationship of loss L and the imaginary part of effective index, $\Im(n_{eff})$, is given by the equation $L = \frac{20}{\ln(10)} \frac{2\pi}{\lambda} \Im(n_{eff})$.

* Corresponding author.
E-mail address: miniyoung@163.com (M.-Y. Chen).

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doi:10.1016/j.optcom.2011.08.062

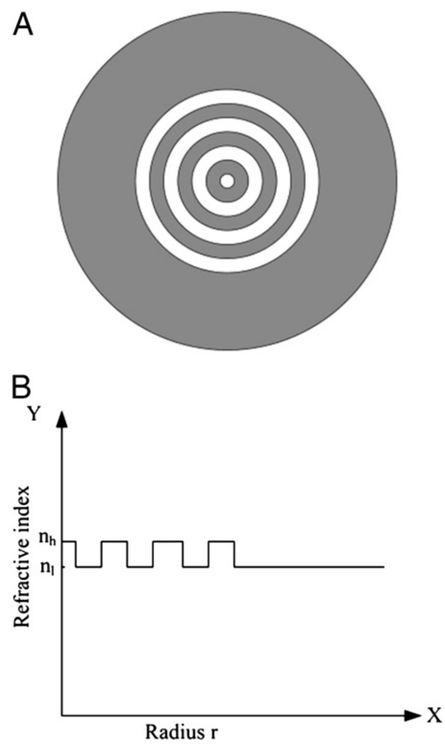

Fig. 1. (A) The cross section of the MROF, (B) refractive index distribution of the MROF along the radial direction.

Fig. 2 show the mode-field profile of the proposed fiber with $r_i = 0.25\Lambda$, $\Lambda = 2.37$, $\Delta = 0.001$, $N = 6$, and $\eta = 1$. The field shows a profile quite similar to that of the conventional optical fiber. The fiber is single-mode guided with the effective mode area as large as 622 μm^2.

We can analyse the MROF by relating the fiber with a step-index optical fiber. The effective core index can be approximated by averaging the square of the refractive index in the core. The concept has been applied to calculate the effective cladding index for photonic crystal cladding in the long-wavelength limit [18]. In this case, the effective core index n_{core} can be determined approximately by

$$n_{core} = \sqrt{\frac{S_c n_c^2 + S_h n_h^2 + S_l n_l^2}{S_c + S_h + S_l}} \quad (1)$$

where S_c,S_h, and S_l, are the areas of the inner core, high-index layers, and low-index layers, respectively. Once the effective index of the core is obtained, the single-mode criterion can be determined

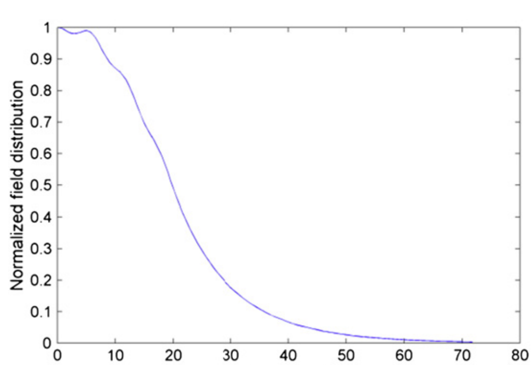

Fig.2. Normalized field distribution of the proposed fiber with $r_i = 0.25\Lambda$, $\Lambda/\lambda = 2.37$, $\Delta = 0.001$, $N = 6$, and $\eta = 1$.

by calculating the normalized frequency V which is defined as $V = \frac{2\pi a}{\lambda}\sqrt{n_{core}^2 - n_b{}^2}$. Where a is the core radius of the fiber. Therefore, single-mode guidance in the fiber requires that the normalized frequency should be less than 2.40483.

We will firstly investigate the influence of the number of layers on the performance of the proposed fiber. The basic structural parameters of the fibers are $r_i = 0.25\Lambda$, $\Delta = 0.001$, and $\eta = 1$. The value of the period Λ is determined by the demand that the cutoff wavelength of the LP_{11} mode in the designed fiber should be just below 1.55 μm, which is achieved by solving modes of the fibers using finite-element method. As shown in Table 1, the cutoff frequency criterion become more accurate for the fiber with more layers in the core, which is owing to the fact the reduction of the period of the layers lead to the more accurate approximation of the effective core index by Eq. (1). It's interesting that we can see the effective fundamental mode index is almost a constant. That is, the effective fundamental index is mainly determined by the index contrast between the high-index layer and the low-index layer. In addition, we can see the effective mode areas of the MROFs with different layer numbers also have little difference even though the core radiuses of the fibers are different. Since the effective index step between the fundamental mode and the cladding determines the sensitivity of a fiber to distortions, this mean that similar characteristics on the bending losses are expected for the MROFs shown in Table 1. Therefore, we can use just a few layers to form an MROF with the desired mode area, so that the manufacturing processes can be simpler.

Increased large-mode area can be realized by keeping the index contrast and using a large η for the layers. Fig. 3 shows the configuration of an MROF with $N = 4$, and $\eta = 2$. Fig. 3(B) shows the mode-field distribution along the radial direction. The mode field shows a dip at the low-index layer region adjacent to the inner core, but still, the overall field has similar mode-field distribution with that of a Gaussian field. The effective mode area of the fiber is 923 μm^2.

Finally, we will discuss the bending characteristics of the proposed fiber. The bending loss curves of a various kinds of SIFs are also plotted as comparison. Bending losses of the fibers are calculated by applying the finite-element method. The bending losses (BL) are calculated by solving the leaky mode of a modified configuration through

$$n(x, y) = n_0(x, y)\left(1 + (1 + \chi)\frac{x}{R_b}\right) \quad (2)$$

where x is the position across the fiber in the direction pointing the bend, $\chi = -0.22$ is a correction due to the elasto-optic effect in pure silica [19] and R_b is the bend radius.

Bending loss curves of two types of MROFs are plotted in Fig. 4. The parameters of MROF A are $r_i = 0.25\Lambda$, $\Lambda/\lambda = 2.37$, $\Delta = 0.001$, $N = 6$, and $\eta = 1$. The parameters of MROF B are $r_i = 0.25\Lambda$, $\Lambda/\lambda = 3.86$, $\Delta = 0.001$, $N = 4$, and $\eta = 2$. The bending loss is lower than 0.02 dB/m for a bending radius great than 20 cm for MROF A. Owing to the reduced index difference between the effective core and the cladding, the bending radius should be larger than 30 cm if the bending loss should be lower than 0.2 dB/m for MROF B. We also plotted the bending losses of three types of SIFs for comparison. The core radius of the core SIF A is set as equal to the core radius of the corresponding MROF, and the refractive index is set as n_{core}, the effective core index of MROF.

As shown in Fig. 4, SIF A generally has a slightly low bending loss than that of the corresponding MROF. Since the two fibers have the same index difference between the effective core and the cladding, it seems that the MROF should have worse bending characteristics than that of SIF. However, it's found that SIF A's have smaller mode areas than those of the MROFs. For example, the mode area of the MROF A and MROF B are 622 μm^2 and 923 μm^2, respectively, whereas