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Single-mode large-mode-area double-ring hollow-core anti-resonant fiber for high power delivery in mid-infrared region

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ABSTRACT

A novel hollow-core anti-resonant fiber with a large mode area and good single mode performance is proposed for high power delivery in mid-infrared region. The structure consists of two-layer circular tubes as the cladding. By optimizing structure parameters, a broad low-loss single-mode band, in which the fundamental mode loss is lower than 4×10^{-3} dB/m and the high order mode extinction ratio (HOMER) is higher than 1000, is achieved in the wavelength region from 2.5 to 3.3 µm in which the lowest loss of 2.87×10^{-4} dB/m occurs at 3.1 µm. The effective mode area is up to 2314 µm^2 with the highest HOMER of 16,600 at the wavelength of 2.8 µm. In addition, this fiber also has good bend resistance characteristics. When the fiber is bent at the bending radius of 18 cm, the mode area reaches to 2268 µm^2 with the HOMER above 100 at the wavelength of 2.8 µm. Furthermore, the effective mode area can be further increased to 4714 µm^2 by increasing core radius at the cost of sacrificing single mode performance and bending resistance.

1. Introduction

Mid-infrared (mid-IR) region covering the wavelength range from 2 to 25 µm, in which there are absorption fingerprints of many gases, water, soil pollutants, components of human breath, and explosive substances [1,2]. Therefore, mid-IR laser has many applications in molecular spectroscopy, remote sensing for environmental monitoring, oil and gas prospecting, and medical diagnostics [3]. Solid-core fiber based on soft glass material is an effective waveguide for mid-IR laser transmission. With the increase of output power of mid-IR lasers, it requires the ability of high power mid-IR pulse delivery in mid-IR fiber. However, it is difficult for solid-core fiber to deliver high power pulse because of material absorption and nonlinear effects, such as Brillouin, Raman, and Kerr effects.

Compared with solid-core fiber, hollow-core fiber guide light in air core, which provide many benefits such as low material absorption, dispersion and nonlinearity, and high damage thresholds [4]. And thus hollow-core fiber has a potential of application for high power pulse delivery [2]. It is important to keep large mode area (LMA) and single-mode transmission in high power pulse delivery. Therefore, implementation of LMA and single-mode transmission at the same time is the key challenge of hollow-core fiber for the application of high power pulse delivery.

It's hard to achieve LMA in hollow-core photonic bandgap fiber (HC-PBGF) due to the structure characteristics. The typical core diameter of HC-PBGF can range from 5 to 35 µm [5]. 3-Cell HC-PBGF can achieve robust single mode guidance and an increase of the number of omitted cells can both increase effective mode area and number of guided modes [6]. The effective mode area of LMA HC-BPGF used in pulse delivery is only 100–200 µm^2 [7,8]. Another hollow-core fiber, hollow-core anti-resonant fiber (HC-ARF), has recently attracted the research interests of scientists because of broad transmission bandwidth, low structure complexity and flexibility in design. Compared with HC-PBGF, HC-ARF can be designed by using a very large core so that a LMA can be achieved for delivering high power pulse [9]. But a challenge for HC-ARF is multi-mode guidance. There is no cutoff condition for high order modes (HOMs) in HC-ARFs and all modes exist at the same time with different losses [4,10]. Therefore, it is an important issue to achieve LMA and suppress HOMs at the same time in HC-ARFs. To qualify the ability of suppressing HOMs in HC-ARF, high order mode extinction ratio (HOMER) is introduced which is defined as the ratio of the lowest loss of HOMs and cladding modes (CMs) to the loss of fundamental mode (FM). When the HOMER in HC-ARF is high enough, it can be regarded as a single mode waveguide.

In 2016, Patrick et al. achieved single mode guidance in HC-ARF by adjusting the diameter ratio of cladding tubes to core region to 0.68 [11]. When the ratio is 0.68, the effective refractive index of LP_{11} modes in core and that of LP_{01} modes in cladding tubes are

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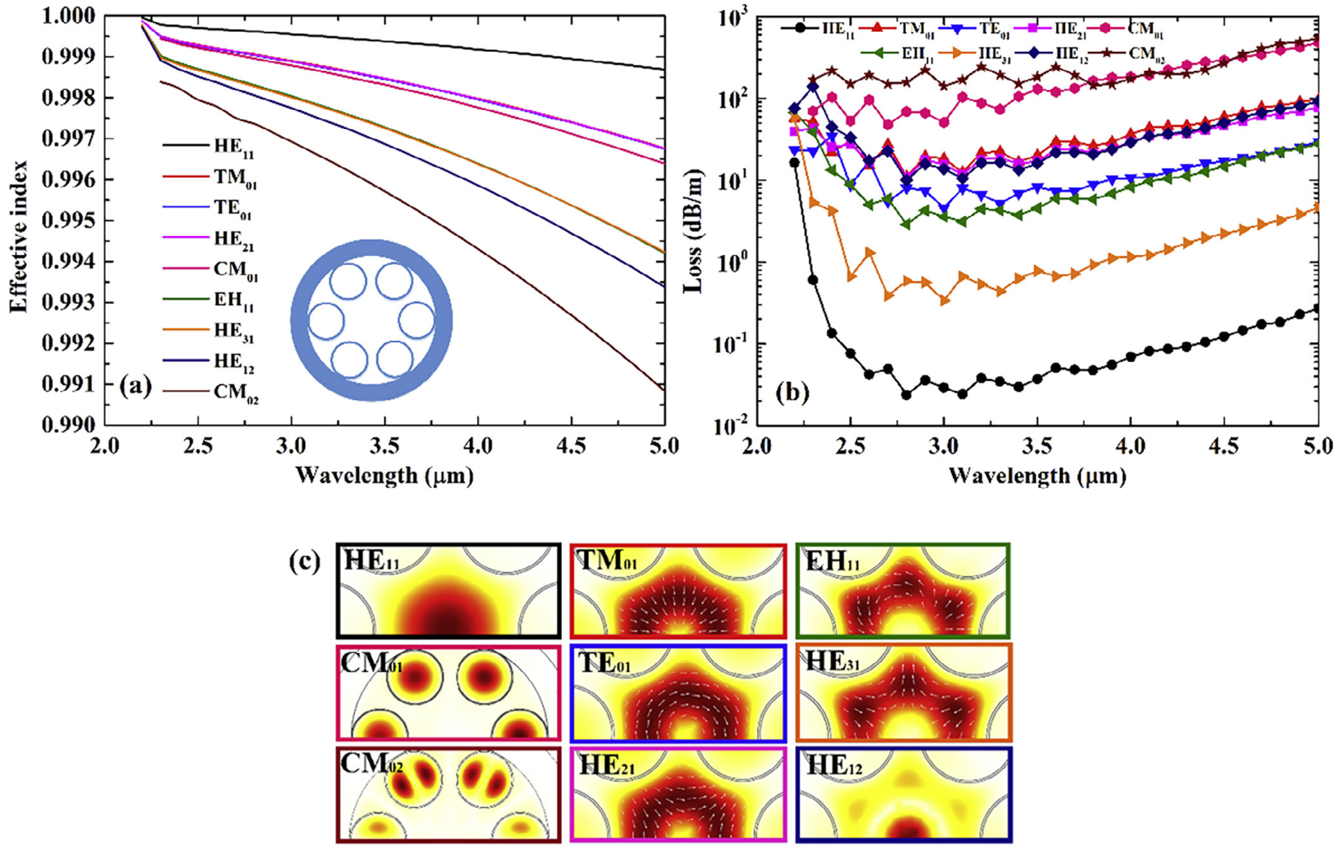

Fig. 1. Effective refractive indexes (a) and losses (b) as function of wavelength and electric field distribution at the wavelength of 2.8 μm (c) of FM, HOMs and CM_s in SRHC-ARF with the core radius of 35 μm and the diameter ratio of cladding tubes to core region of 0.68.

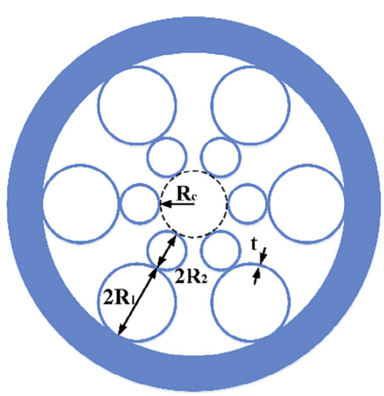

Fig. 2. Cross section of the proposed fiber with ZBLAN glass as the background material.

approximately equal, which causes to strong coupling between these modes and make LP_{11} modes being strongly suppressed. But this way cannot suppress LP_{21} modes or higher-order modes. In Ref. [11], the highest loss ratio of LP_{11} mode to FM is up to ~1200 but the average loss ratio of LP_{21} mode to FM is only ~70.

Another way to achieve single mode guidance is using elliptical tube as the cladding. In 2016, Selim et al. proposed an elliptical tube HC-ARF with a high HOMER of ~2500 and a low loss of ~0.006 dB/m at 1.06 μm [12]. In 2017, Meng et al. proposed a nested elliptical tube HC-ARF with a very high HOMER of ~20000 and a low loss of ~10^{-5} dB/m at 800 nm [13]. Nested elliptical tube structure can provide excellent performance compared with circular structure, but low fabrication feasibility restricts the implementation of nested elliptical tube HC-ARF.

In this paper, we propose a novel double-ring single-mode LMA HC-ARF including double layer circular tubes as the cladding. The finite-element-method with perfectly matched layer boundary conditions is used to simulate the transmission characteristics. Numerical results show that a broad low-loss single-mode band is achieved in the wavelength region from 2.5 to 3.3 μm in which the FM loss is lower than 4×10^{-3} dB/m and the HOMER is higher than 1000. The effective mode area is up to 2314 μm^2 at the wavelength of 2.8 μm. This fiber also has strong bend resistance. Furthermore, the effective mode area can be further increased to 4714 μm^2 by increasing core radius at the cost of bending resistance and HOMER. The structure of the proposed fiber and the comparison between single-ring structure and double-ring structure are presented in Section 2. The discussions of structure parameters on the characteristics of the proposed fiber are given in Section 3. Finally, conclusions are summarized in Section 4.

2. Structure and comparison

First, we investigate if the single-ring HC-ARF (SRHC-ARF) can achieve both single mode guidance and a large effective mode area simultaneously. The structure of SRHC-ARF with a large core radius of 35 μm is shown in the inset of Fig. 1(a) and the ratio of diameter of cladding tubes to diameter of core region is 0.68. Background material is ZBLAN glass and tube thickness is 1 μm. The resonant wavelength can obtained by $\lambda_m = 2t\sqrt{n^2-1}/m$ [14], where n is the refractive index of background material, m equals any positive integer and t is the tube thickness. When $m = 1$, the first resonant wavelength is 2.2 μm. The confinement loss is deduced from the value of n_{eff} as $CL = 8.686k_0\mathrm{Im}(n_{eff})$ [15], where $k_0 = 2\pi/\lambda$ is the wave vector. Fig. 1(a) and (b) show the effective indexes and losses of FM, six HOMs (TM_{01}, TE_{01}, HE_{21}, EH_{11}, HE_{31}, and HE_{12}) and two CMs (the FM and LP_{11} mode in cladding tubes) as function of wavelength in SRHC-ARF. Fig. 1(c) shows the