High Performance Large Mode-Area Ytterbium-doped Photonic Crystal Fiber for Fiber Lasers

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Abstract. In this letter, large-mode-area double-cladding ytterbium-doped photonic crystal fiber was designed in theory and fabricated in practice. This fiber we have fabricated successfully has endless single mode operation performance and large inner-cladding numerical aperture of more than 0.75. The struts width between large air-holes in the outer-cladding is about 0.22 \(\mu m\). The photonic crystal fiber has a mode-area about 1465.7 \(\mu m^2\). Due to the material being pure silica and air, such structures have excellent capacity to withstand high temperature. The laser light can have very good beam quality, even diffraction-limited beam quality because of the single-mode core. This fabrication technical breakthrough of novelty high performance double-cladding ytterbium-doped photonic crystal fibers will give contributions to the high power fiber lasers and promote the progress of technology in the fields of high power lasers.

1. Introduction

High power fiber lasers and fiber amplifiers are the research frontier in the fields of lasers at present. They are nearly always realized with rare-earth-doped double-cladding optical fibers [1-4], which are pumped with fiber-coupled high-power diode bars or other kinds of laser diodes. The pump light is launched into an inner cladding rather than into the much smaller fiber core, in which the laser light is generated. Conventional double-cladding optical fibers are based on step-index type of core designs and polymer-based outer-cladding materials to create an inner cladding with a high numerical aperture (NA). These fibers provide core size of up to around 10 \(\mu m\) to 30 \(\mu m\) for single mode to few modes operation. With large core sizes, these kinds of active fibers can handle power levels to the kW level. However, the laser beam quality and laser brightness with these fibers is not ideal, and the bending loss of these active fibers is big. Besides, the use of polymers limits the heat-handling capacities of the active fibers for high power fields.

To tackle these problems, many solutions have been taken. Among them, bending methods were taken to improve beam quality. The double cladding active fiber was bent with a diameter of about 20 cm to reduce bending loss for higher-order modes without affecting the fundamental mode [5]. But the bending leads some power leaking into the polymer outer-cladding, which results the softening and failing of the polymer cladding. P. Wang et al [6] demonstrated a approach to achieve nearly single-mode operation in a cladding-pumped multimode-core fiber laser based on the use of a fiber with helical-core geometry. All these methods cannot maintain robust and efficient single-mode operation.
J. Limpert et al. [7-12] made laser experiments for robust single-transverse-mode propagation with double-cladding ytterbium-doped photonic crystal fibers (PCFs). In this letter, double-cladding ytterbium-doped photonic crystal fiber was designed and fabricated. This fiber has ultra low core numerical aperture (NA) for making very large, strictly single mode core, and very high inner-cladding NAs for making high coupling efficiency.

2. Theoretical Design

For PCFs, the Micro-hole arrays are distributed regularly in the PCFs, these periodical micro-hole arrays make great action on the transmission light. The shorter the transmission light wavelength is, the more centralized to the higher index domain the light intensity is, so the effective refractive index of the cladding will be raised. The cladding effective refractive index is decided by the Fundamental Space-filling Modes (FSMs) in the microstructure optical fiber, $\beta_{FSM}$ is defined as the transmission constant of the FSMs. Therefore, the effective refractive index of fiber cladding $n_{eff}$ could be written as [13,14]:

$$n_{eff} = \frac{\beta_{FSM}}{k}$$

$\Lambda$ is the micro-hole pitch. When $\lambda \rightarrow 0$, the mode field distributions of the transmission light don’t change basically, they don’t depend on the light wavelength and the hole’s distance, but are related to the relative dimension between the diameter of micro-hole ($d$) and transmission wavelength ($\lambda$). When $\nu_{pfc} < \pi$, light could transmit in the photonic crystal fibers in the single mode way [15,16]. The relations between normalized transmission frequency ($\nu_{pfc}$) of the photonic crystal fibers at different $d/\Lambda$ and the $\Lambda/\pi$ were theoretically calculated. The Figure 1 shows the theoretical results.

Light could transmit along the photonic crystal fibers in the single mode way, when the $d/\Lambda < 0.30$ and $\Lambda$ is as big as fifteen times of $\lambda$. While $d/\Lambda > 0.45$, the maximum ratio of $\Lambda$ to $\lambda$ is 1.538, light can be also guided in the state of single-mode.

![Figure 1. The relation between $v_{eff}$ and $\Lambda/\lambda$.](image)

The numerical aperture of the inner cladding ($NA_{iclaid}$) is relative to the refractive index of inner cladding and the refractive index of fundamental bridge mode in the air-silica compounded outer cladding ($n_b$). The $NA_{iclaid}$ can be calculated from the following equation.

$$NA_{iclaid} = \sqrt{n_b^2 - n_{silclaid}}$$

Figure 2 shows the air-clad structure, it includes air-holes and silica bridges. The $n_b$ is dependent on the width of the bridge ($b$) and the radial-width of the large air-holes ($w$) in the air-silica compounded outer-cladding. The direction of power propagation in bridge modes has radial and longitudinal components. In the limit of $w/ \rightarrow \infty$, a continuum of these modes exists with effective indices in the range between 1 and $n_v$. The effective index $n_v$ is therefore an upper bound for all such localized bridge modes that have a radial component to power propagation. In order to separate the leakage mechanisms of loss via
the bridges from that of optical tunneling, the extreme situation of $w/\lambda >> 1$ is assumed. The upper bounds of $N_{A_{\text{iclad}}}$ are valuable for choosing the radial width of air-clad designs. It suggests that, when $w/\lambda > 4$, the role of optical tunneling in influencing the NA can be neglected for all practical lengths [17]. In our simulation, $w/\lambda = 10$ and $\lambda = 915\text{nm}$ are assumed, and the results are shown in Fig. 3. The smaller the bridge width is, the bigger the $N_{A_{\text{iclad}}}$ is. When the $b/\lambda << 1$, the $N_{A_{\text{iclad}}}$ is close to 1. The relation between the bridge width and the $N_{A_{\text{iclad}}}$ is shown in Fig. 3 by simulation.

3. Fabrication and Results

By the method of Stack & Drawing, the double-cladding ytterbium-doped photonic crystal fiber (DY-PCF) was fabricated successfully, which was shown in the Fig. 4. The fiber has a 43.22-$\mu$m diameter ytterbium-doped core with a numerical aperture of 0.06. In the inner cladding, the air-filling fraction is 30%. In the outer cladding, the radial width of the large hole size is 19.5-$\mu$m, and the bridge thickness between the adjacent air-holes is 0.22-$\mu$m, which is shown in Fig. 5. At the wavelength of 1.06-$\mu$m, the $w/\lambda = 18.4 >> 1$, $b/\lambda = 0.21 << 1$. Therefore, the structure parameters meet the conditions of single-mode operation and big $N_{A_{\text{iclad}}}$. The fiber has a 1465.7-$\mu$m² mode area and a $N_{A_{\text{iclad}}}$ of 0.75 by our measurements. This measuring NA of the inner-cladding is 20% smaller than the theoretical value of 0.95, the difference is due to test windage of the Far-field light distribution.

Figure 6 shows the simulation results of the power distribution in the DY-PCF. From the figure, we can see that the fundamental mode light is restricted tightly in the ytterbium-doped core.

Figure 2. The air-clad structure of the PCF.  

Figure 3. The relation between bridge width and NA of inner cladding.  

Figure 4. The SEM photo of DY-PCF.  

Figure 5. The SEM photo of silica bridge.
4. Conclusions
In this letter, the large-mode-area double-cladding ytterbium-doped photonic crystal fiber was designed in theory and fabricated in practice. This fiber has endless single mode operation performance and large inner-cladding numerical aperture of more than 0.75. The photonic crystal fiber has a mode-area about $1465.7 \mu m^2$. Due to the material being pure silica and air, such structures have excellent capacity to withstand high temperature. The laser light can have very good beam quality, even diffraction-limited beam quality because of the single-mode core. This fabrication technical breakthrough of novelty high performance double-cladding ytterbium-doped photonic crystal fibers will give contributions to the high power fiber lasers and promote the progress of technology in the fields of high power lasers.

Acknowledgments
This work is supported by the National Basic Research Program of China (Grant No. 2003CB314905 and 2010CB327606), the National Key Basic Research Special Foundation (Grant No. 2006CB806006) and the National High Technology Research and Development Program of China (Grant No. 2007AA03Z447 and 2008AA03Z405).

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