Improved large-mode-area Bragg fiber

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A novel large-mode-area Bragg fiber (BF) is proposed for selectively suppressing the amplified spontaneous emission (ASE) of Yb. Confinement loss can be effectively lowered by adding a layer of F-doped glass near the core of this fiber. The BF can achieve effective suppression of ASE of Yb when the bend radius is 0.15 m at wavelength lower than 1.13 μm in theory, and eliminate LP_{11} mode in mode competition in wavelength range of 1.15−1.2 μm.

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Two-dimensional (2D) solid-core photonic bandgap fibers (SC-PBGFs) have attracted much attention over the past few years because of their unusual dispersion and modal properties[1−4]. Moreover, such fibers can be used as wavelength-dependent distributed filters owing to the band gap principle. By filtering the amplified spontaneous emission (ASE) of Yb in the high-gain region (∼1.03−1.1 μm), the frequency-shifted fiber laser (FSFL) can achieve high output power (∼0.98 or 1.15 μm)[5−9], which provides a new means of blue or yellow light generation by direct frequency-doubling FSFL. In 2009, Shirakawa *et al.* obtained 30-W laser at a wavelength of 1178 nm with a double-clad Yb-doped SC-PBGF, and pointed out two main problems in such fibers[9]. Firstly, the Ge-doped lattice in the clad absorbed an amount of pump power. Secondly, with the Yb-doped SC-PBGF, it was difficult to achieve large-mode-area (LMA) design. Both factors impede further improvement of the output power of FSFL.

Bragg fibers (BFs) consist of a core with low refractive index, surrounded by alternating layers with high and low refractive indices[10]. Light confinement in the core is due to the coherent Fresnel reflection from the boundaries between the high-index and low-index layers. BFs are promising candidates for designing LMA structures owing to their high bend immunity[11]. Continuous wave and mode-locking oscillations have recently been demonstrated around ∼1.06 μm in the Yb-doped BF lasers[12,13]. Thus, the LMA BF with a core diameter of 30 μm is a candidate for high-power FSFL, and is compatible with common Yb-doped active fiber and optical devices. In this study, we propose a novel bend-resistant LMA BF for filtering the high-gain region of Yb ASE. The low-index F-doped layer added near the core can enhance the light confinement. In theory, the BF can effectively suppress the ASE of Yb at wavelength lower than 1.13 μm at a bend radius of 0.15 m. The large difference in confinement loss (CL) between LP_{01} and LP_{11} modes is beneficial for achieving single-mode oscillation in laser cavity.

The cross section and refractive index profiles of the improved BF are shown in Fig. 1. Unlike common BFs, this BF has a thin F-doped layer added adjacent to the fiber core to decrease the bending loss. The fiber core has a diameter (D_{co}) of 30 μm, and its refractive index difference, compared with pure silica (n_{S}=1.45), is $\Delta n_{\mathrm{co}}=3\times10^{-4}$. The thin F-doped layer has a thickness of 3 μm, and its refractive index difference is $\Delta n_{\mathrm{F}}=4\times10^{-3}$. Three coaxial high-index Ge-doped rings compose the Bragg mirror. The thickness and pitch of these rings are 1.5 and 12 μm, respectively. Each ring has an index difference of $\Delta n_{\mathrm{Ge}}=4.5\times10^{-3}$ higher than that of pure silica.

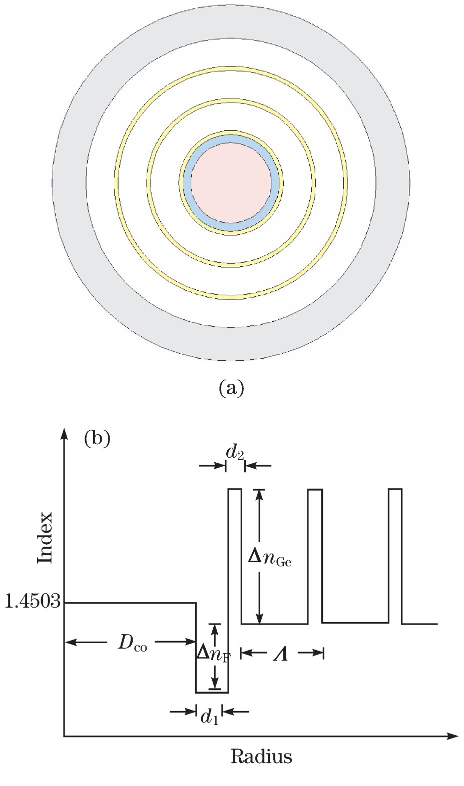

Fig. 1. (a) Cross section and (b) refractive index profiles of improved BF.

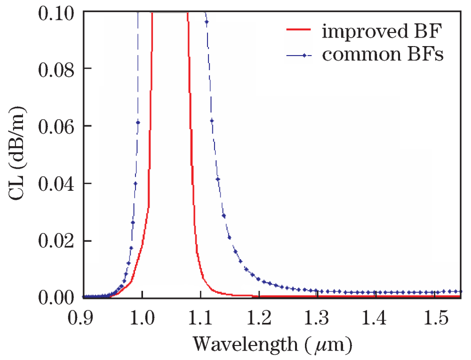

Fig. 2. Calculated CL curves of improved and common BFs.

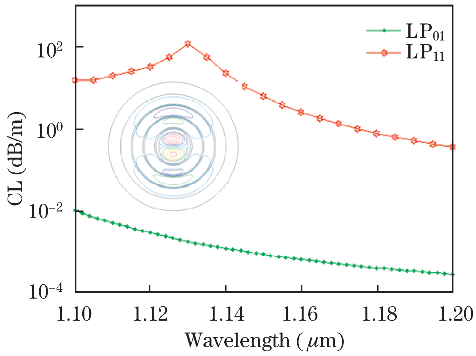

Fig. 3. Calculated CL curves of LP_{01} and LP_{11} modes of the improved BF. The inset is LP_{11} mode distribution at 1.13 μm.

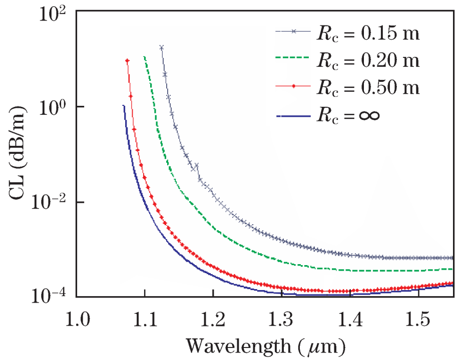

Fig. 4. Dependence of CLs on bend radius.

The CL is calculated by Comsol 3.4. Figure 2 shows the CL of fundamental LP_{01} mode as a function of wavelength for the improved BF (solid line). Its high-loss region lies between 1.02 and 1.08 μm, and the loss edge is steep enough for suppressing the segmental ASE of Yb ion, in accordance with the design goal. For comparison, the CL of a common BF with the same fiber structure and with no F-doped layer is calculated and shown as the dotted line. It can be seen that the improved BF has a smaller loss in band gap than the common BFs. Therefore, by carefully designing the thickness and index difference of the F-doped layer, the improved BF can still maintain band gap property and achieve lower propagation loss, which is very helpful for laser oscillation in the range of 1.15−1.2 μm. To verify the mode properties of the improved BF, we calculate the CL of LP_{01} and LP_{11} modes in the range of 1.1−1.2 μm. The CL difference of the two modes is at least three orders of magnitude (Fig. 3). The CL curve of LP_{01} mode decreases smoothly, whereas the CL curve of LP_{11} mode has a projection around 1.13 μm. The inset in Fig. 3 is the calculated mode distribution at 1.13 μm. The strongest coupling is observed between the LP_{11} mode and the modes in the Bragg mirror, giving rise to a maximal loss of LP_{11} mode.

Bending SC-PBGF can effectively change band gap edge and CL, especially for LMA fiber. The bending properties of fibers can be estimated using the equivalent index[14] $n_{\text{eff}} = n \times \exp(\frac{x}{R_c})$, where R_c is the bend radius and n is the refractive index. Our calculation shows that bending the fiber tightly can increase CL and shift loss edge distinctly to longer wavelength (Fig. 4). When R_c = 0.15 m, the calculated CL is ∼5, 0.24, and as low as 0.014 dB/m at 1.13, 1.15, and 1.2 μm, respectively. The calculated LP_{01} mode at 1.13 μm demonstrates strong coupling with Bragg mirrors; in contrast, the modal coupling is quite weak at 1.2 μm (Fig. 5). Hence, this BF can effectively filter the ASE of Yb at wavelength lower than 1.13 μm to eliminate parasitic oscillation, and achieve lasing in the range of 1.15−1.2 μm when R_c = 0.15 m. To verify the single-mode property, the CL of LP_{01} and LP_{11} modes at R_c = 0.15 m are calculated (Fig. 6). The LP_{11} mode, which has the calculated CL larger than 20 dB/m in the range of 1.15−1.2 μm, would be suppressed by LP_{01} mode in the laser cavity. In this case, the fundamental LP_{01} mode at 1.18 μm has a mode field area of about 410 μm^2 and an optical loss of less than 0.03 dB/m.

In conclusion, an improved BF is proposed for tailoring ASE gain spectrum. Although designed in a large-core configuration, this BF still has a high-loss region in the range of 1.02−1.08 μm with steep gap edge for suppressing the ASE effectively. The introduced F-doped

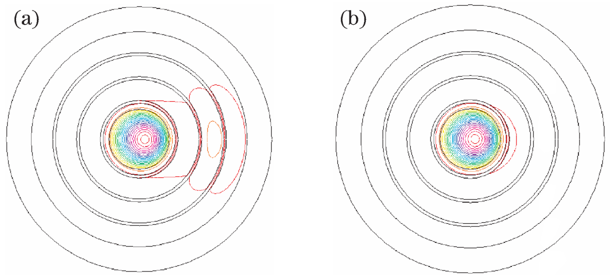

Fig. 5. LP_{01} mode distribution at (a) 1.13 and (b) 1.2 μm.

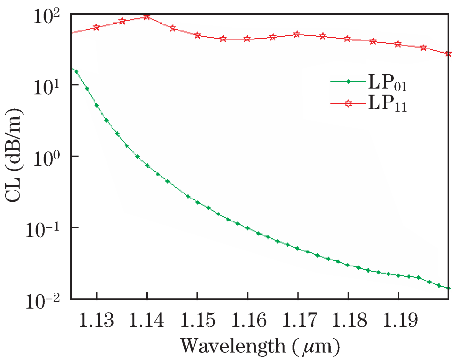

Fig. 6. CLs of LP_{01} and LP_{11} modes at R_c = 0.15 m.

layer can lower the CL. Our calculation shows that the CL is very low in the wavelength range of 1.15−1.2 μm at $R_c = 0.15$ m. The novel fiber design is of great significance for the high-power FSFL and the highly efficient yellow laser light generation.

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