Simple suppression technique for higher-order mode amplification in bent large mode area triple-cladding fibers

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Abstract: A novel technique to suppress the higher-order mode in bent LMA triple-cladding fibers is proposed. It is shown that the higher-order mode can be coupled to a cladding mode with only an adjustment of the bending diameter.

OCIS codes: (060.2280) Fiber design and fabrication; (060.2400) Fiber properties.

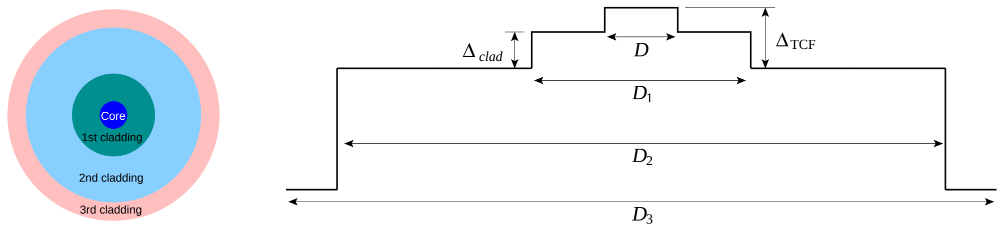
1. Introduction

Recently, high-power fiber lasers and amplifiers have had remarkable progress [1]. To increase the output power, optical fibers with a strong tolerance to high optical power are highly required, since the high optical power density results in a degradation of laser/amplifier operation due to nonlinear phenomena such as Raman scattering, Brillouin scattering, and similar ones. In order to reduce the nonlinear effects and increase the output power, an enlargement of the effective core area is beneficial; therefore various kinds of large mode area (LMA) fibers have been reported so far. The simplest way to achieve LMA optical fibers is to employ step-index fibers with a large core and a low numerical aperture (NA) to suppress the multi-mode behavior typical of such large-core fibers at the price of a significant increase of the macro-bending loss. This can be addressed through the deployment of specially-designed optical fibers with higher NA that can achieve an effectively single-mode operation regime by limiting the propagation of the higher-order modes. However, while in the standard fibers the core diameter cannot be raised over 30 μm due to the onset of multi-mode behavior [2], if we consider the all-silica photonic crystal fibers (PCFs), which would permit to obtain very broad-band single-mode LMA operation, a very similar diameter limit is encountered due to the increase of the bending losses [3]. The employment of leakage channel fibers (LCFs) [4], characterized by a cladding formed by a single air-hole ring, is one of the approaches proposed to realize effectively single-mode LMA fibers, however, as LCFs are inherently lossy structures that only support leaky guided modes, it is difficult to develop low loss and low bending loss fiber lasers/amplifiers. Another promising way to achieve LMA fibers is to employ resonant structures, such as ring-assisted fibers [5] and chiral fibers [6], however, their refractive index profiles are very complicated and an accurate control of the index profile is required, resulting in fabrication issues and high fabrication cost.

In this work, we propose and numerically investigate a novel technique to suppress the higher-order mode in bent LMA fibers. We consider a simple triple-cladding fiber (TCF) with step-index profile and evaluate the overlap factor between the higher-order mode and the core region as a function of the bending diameter. Through a detailed modal analysis based on the finite element method, it is shown that the higher-order mode can be coupled to a cladding mode in the first cladding with only an adjustment of the bending diameter, while keeping a strong confinement of the fundamental mode with low bending loss in the 1 micron wavelength range. The higher-order mode suppression can be achieved in a bandwidth wider than 10 nm without a complicated fiber structure and precise control of the index profile.

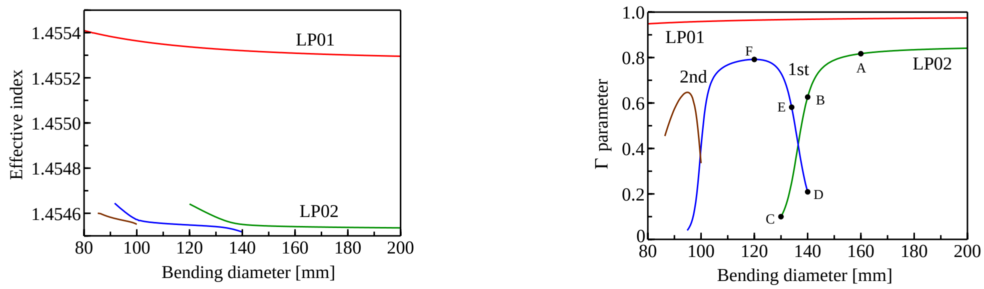
2. Triple-Cladding Fiber Design and Bending Characteristics

Figure 1(a) shows a schematic cross section of a triple-cladding LMA fiber considered here, where the core diameter D is 30 μm, the first cladding diameter D_1 is assumed to be a variable parameter, and the second and third cladding diameters, D_2 and D_3, are 400 μm and 450 μm, respectively. Figure 1(b) shows the refractive index profile of the TCF, which is a simple step-index profile. The second cladding is assumed to be pure silica with refractive index of 1.44963 at 1064 nm wavelength, while the relative refractive index difference between the core and the second cladding is Δ_{TCF}, the one between the first and the second cladding is Δ_{clad}, and the third cladding is a low index polymer material with refractive index of 1.376, since we are designing it for application in Yb-doped high power fiber lasers and amplifiers. The merit of the TCF with respect to a double-cladding fiber, which is a popular structure for fiber laser applications, is the improvement of the pump light efficiency. A large-diameter second cladding enables to increase the pumping light power. The high power pumped to the second cladding concentrates in the first cladding thanks to Δ_{clad}. If the refractive index difference between the core and the first cladding is low enough and its NA is lower than 0.027, the TCF is single-mode at 1064 nm. However, in that case, the bending loss is very high even for the fundamental mode and it is difficult to construct compact fiber lasers or amplifiers, so we consider a TCF with low bending loss which supports several core guided modes.



(a) (b)

Fig. 1. (a) A schematic cross section of the proposed triple-cladding large-mode-area fiber and (b) its simple step-index profile.



(a) (b)

Fig. 2. The bending diameter dependence of (a) the effective refractive indices of the LP_{01} and LP_{02} modes and (b) the overlap factor Γ between the guided modes and the core region (Yb-doped region) in the triple-cladding fiber shown in Fig. 1, where D=30 µm, D_1=90 µm, Δ_{TCF}=0.40 %, Δ_{clad}=0.30%, and operating wavelength is 1064 nm.

Figure 2(a) shows the effective refractive indices of the two axially-symmetric LP_{01} and LP_{02} modes, as a function of bending diameter at 1064 nm wavelength, calculated by the full-vector finite element method [7], where D_1=90 µm, Δ_{TCF}=0.40 %, and Δ_{clad}=0.30 %. The LP_{03} mode or higher axially-symmetric core modes are not guided by this TCF in the 1 micron wavelength range. It is known that the excitation of the axially-asymmetric modes can be avoided by appropriately splicing the fiber, therefore a suppression technique for the axially-symmetric LP_{02} mode is very important. The effective index of the LP_{01} mode monotonically increases as the bending diameter decreases, while we can find two anti-crossings on the index curve of the LP_{02} mode at specific bending diameters in this range. The steep index curves correspond to cladding modes confined in the first cladding and propagating in the bent fiber, and these cladding modes couple with the LP_{02} mode at specific bending diameters, resulting in the localized suppression of the LP_{02} mode amplification. Figure 2(b) shows the bending diameter dependence of the overlap factor Γ between the guided modes and the core region (Yb-doped region) defined as:

$$\Gamma = \int_{core} |\phi(x,y)|^2 dxdy \Big/ \int |\phi(x,y)|^2 dxdy\,, \qquad (1)$$

where D_1=90 µm, Δ_{TCF}=0.40 %, Δ_{clad}=0.30 %, and the operating wavelength is 1064 nm. The Γ parameter of the LP_{02} mode decreases at two different bending diameters corresponding to the two anti-crossing points in Fig. 2(a), while the Γ parameter of the LP_{01} mode maintains values higher than 0.95. The first anti-crossing at the bending diameter of ~140 mm occurs due to the coupling between the LP_{02} mode and the first-order cladding mode, while the second anti-crossing around 100 mm bending diameter is due to the second-order cladding mode. It is worth noting that the bending diameter where the anti-crossing occurs can be shifted to larger values and the decrease of the Γ parameter becomes sharper as the first cladding diameter increases, since the effective index of the cladding mode propagating in the first cladding of the bent fiber increases and the coupling between the LP_{02} core mode and the cladding mode weakens for increasing diameter of the first cladding. In order to visualize the coupling phenomenon, Fig. 3 shows the LP_{02} mode field distributions at different bending diameters indicated in Fig. 2(b) as A to F. From these results, we can say that the suppression of the LP_{02} mode amplification can be simply controlled by the bending diameter.

Figure 4(a) shows the first cladding diameter dependence of the resonant bending diameter in which the LP_{02} mode is coupled with the cladding modes in the first cladding, where Δ_{TCF}=0.40 %, Δ_{clad}=0.30 %, and operating wavelength is 1064 nm. The green line corresponds to the coupling to the first-order cladding mode, while the blue and brown lines correspond to the second- and third-order cladding modes, respectively. The resonant bending diameter is linearly increasing as the first cladding diameter increases, therefore the suppression of the higher-order mode can also be controlled by the first cladding diameter. In addition, by increasing the first cladding diameter, the number of cladding modes which can be coupled with the LP_{02} mode increases. However, it can be noticed that the coupling coefficient between the lower-order cladding mode and the LP_{02} mode becomes smaller and the bandwidth of Γ parameter suppression for the LP_{02} mode becomes narrower as the first cladding diameter is enlarged.

Figure 4(b) shows the wavelength dependence of the Γ parameter of the LP_{02} mode, where D_1=90 μm, Δ_{TCF}=0.40 %, Δ_{clad}=0.30 %, and the bending diameter is 13.6 cm. The green curve corresponds to the LP_{02}-like mode with higher effective index around the anti-crossing point, while the blue curve corresponds to the lower index one. We can clearly see that the Γ parameter of the LP_{02} mode is strongly reduced around 1064 nm wavelength range and the bandwidth where the Γ parameter is lower than 0.5 is larger than 10 nm, therefore we can say that the coupling phenomenon is not so sensitive to the bending diameter and the suppression of the LP_{02} mode amplification in the TCF bent to resonance can be easily observed experimentally.

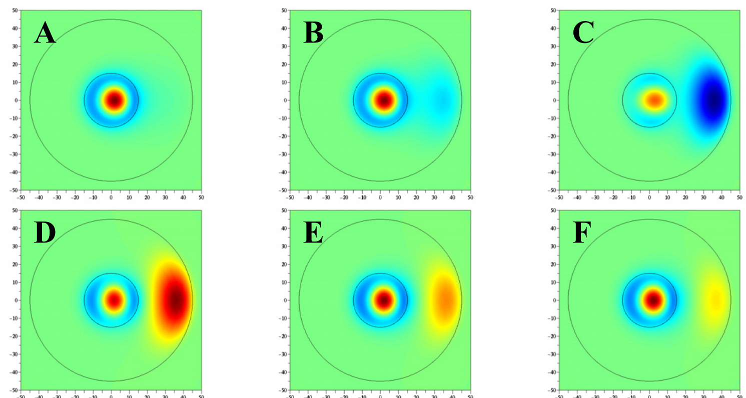


Fig. 3. The LP_{02} mode field distributions at different bending conditions indicated in Fig. 2(b) as A to F.

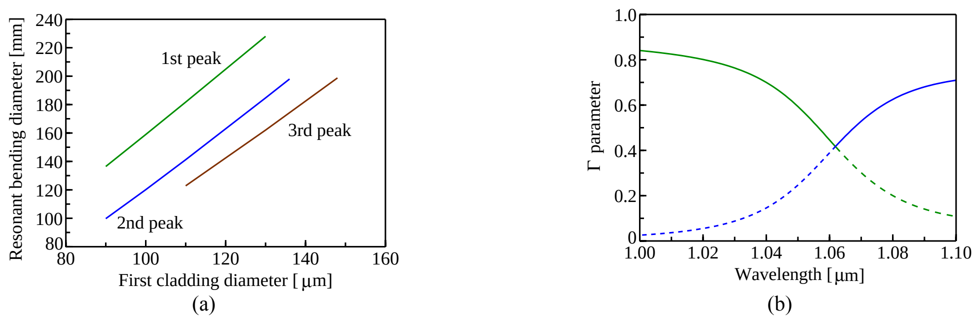


Fig. 4. (a) The first cladding diameter dependence of the resonant bending diameter for which the LP_{02} mode is coupled with the cladding modes in the first cladding at 1064 nm wavelength and (b) the wavelength dependence of the Γ parameter of the LP_{02} mode at the bending diameter of 13.6 cm.

3. Conclusion

The bending characteristics of the newly designed triple-clad LMA fiber with a step-index profile have been investigated. It is shown that the overlap factor of the higher-order mode can be suppressed by simply bending the fiber at the resonant bending diameter, while the fundamental mode is well confined in the Yb-doped region. The proposed suppression technique for the higher-order mode amplification in a bent multi-cladding LMA fiber will be suitable for constructing compact and low-cost high power fiber lasers and amplifiers. An experimental verification is now under consideration.

4. References

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