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Pump absorption in coiled and twisted double-clad hexagonal fiber: effect of launching conditions and core location

Romain Dalidet^b, Pavel Peterka*^a, Valérie Doya^b, Jan Aubrecht^a, and Pavel Koška^a

^aInstitute of Photonics and Electronics of the Czech Academy of Sciences, Chaberská 57,
18251 Prague, Czech Republic

^bUniversité Côte d'Azur, CNRS, Institut de Physique de Nice site Valrose, UMR 7010, Parc Valrose,
Nice, Cedex 2, France

ABSTRACT

Ever extending applications of fiber lasers require energy efficient, high-power, small footprint and reliable fiber lasers and laser wavelength versatility. To meet these demands, next generation of active fibers for high-power fiber lasers is coming out that will eventually offer tailored spectroscopic properties, high robustness and reduced cooling requirements and improved efficiency through tailored pump absorption. We report on numerical modelling of the efficiency of the pump absorption in double clad active fibers with hexagonal shape of the inner cladding cross section and rare-earth-doped core. We analyze both the effect of different radii of the spool on which the fiber is coiled and different fiber twisting rates. Two different launching conditions were investigated: the Gaussian input pump beam and a speckle pattern that mimics the output of the pump laser diode pigtail. We have found that by asymmetric position of the rare-earth-doped core we can significantly improve the pump absorption.

Keywords: fiber lasers, fiber design and fabrication, optical pumping

1. INTRODUCTION

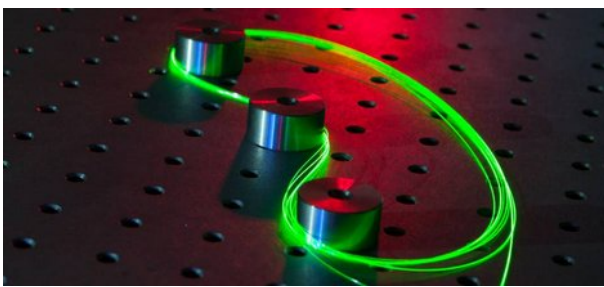
Fiber lasers are generally considered as one of the youngest and most rapidly developing branch of lasers. In fact, we may observe waves of increased interest in fiber lasers in time driven by various motivations and societal conditions [Okhotnikov2012, Richardson10, Peterka17]. Nowadays, we are witnessing new wave of interest in fiber lasers that coincide with emerging new applications in many areas of human activities, including new fast manufacturing processes (e. g., for the so called factories of the future), robot-based processing, processing of new materials/organic electronic, solar cell mass production, healthcare, light sources in biophotonics, environmental control and security applications [Taccheo16]. For the new applications of fiber lasers, the race for the highest power is usually not the priority, but the fiber laser devices with tailored performance, e. g., unconventional wavelengths, tailored beam shape, small footprint, high efficiency, are often required. To meet these demands, next generation of active fibers for high-power fiber lasers is coming out that will eventually offer tailored spectroscopic properties [Baker17, Blanc17, Kasik14], high robustness and reduced cooling requirements [Daniel17] and improved efficiency through tailored pump absorption [Koška17, Zervas17].

In this paper, we report on numerical modelling of the efficiency of the pump absorption in double clad active fibers with hexagonal shape of the inner cladding cross section and rare-earth-doped single-mode core. The propagation of the multimode pump radiation along the double-clad fiber is simulated using fast-Fourier transformation (FFT) method and beam-propagation method (BPM) [Doya01, FeitFleck80, Koška16, references to be modified/added]. Conformal transformation of the refractive index profile is applied in order to account for the simultaneous coiling and twisting of the fiber [Koska15, Koska16]. The effects of different radii of the spool, fiber twisting rate and launching conditions are investigated.

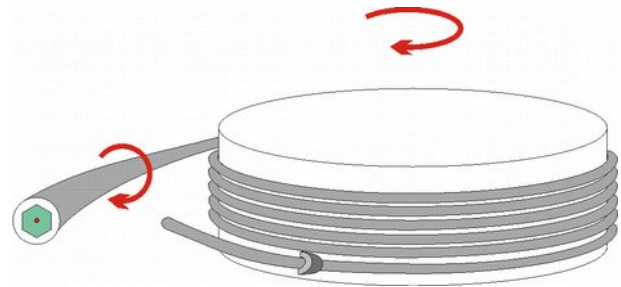
*peterka@ufe.cz; phone +420 266 773 527; fax +420 284 680 222; www.ufe.cz

2. THEORETICAL MODEL

Beam propagation method is well known and accurate way to simulate the propagation of light inside optical wave guides [FeitFleck80]. Fast Fourier transform (FFT) is preferred to Crank-Nicolson or finite difference method because of its more accurate stability and its possibility to add non-linearity. This method can also be used to simulate the propagation of the pump and signal inside doped fibers. In double-clad fibers, the pump light is coupled into the inner cladding, while the signal is amplified inside the doped core. Within the pump propagation, the core will gradually absorb the pump, thus driving the amplification process. This kind of fibers have shown great success in applications and enabled high-average-power laser fibers. The choice of the refractive index profile can be a determining parameter regarding the absorption. Indeed, some modes will never interact with the core. For example, LP modes in a circular multimode fiber with a positive azimuthal index may not be coupled with the core. Using a geometrical point of view, some rays called skew rays will completely avoid the core, even after multiple reflections. To avoid those phenomena, one can consider modifying the geometry of the fiber, using truncated, stadium, hexagon, octagon and other shapes of the fibers inner cladding cross section, which will lead to a more uniform distribution of the light field and generate chaotic rays, allowing a more efficient use of the pump light [Doya01]. The pump absorption can be enhanced also by improvement of the mode mixing inside the inner cladding thanks to special coiling method, e. g., by figure eight or kidney-shape coils, see Fig. 1(a) or by simultaneous coiling and twisting on a standard round-shape type of the spool, see Fig 1(b) [Kořka16a].



(a)



(b)

Figure 1. Examples of special coiling methods used for improving the mode-mixing and correspondingly the pump absorption in double clad fibers: (a) kidney shape coil and (b) simultaneous coiling and twisting of the active fiber.

We use here the FFT-BPM to study the pump propagation inside a hexagonal double-clad fiber, doped with ytterbium. Unless otherwise indicated, parameters of the fiber used in simulations are listed in Table 1. The edges of the hexagon as well as the interface between core and the inner cladding are smoothed in order to avoid numerical issues that can appear using FFT method with abrupt discontinuities of the refractive index.

Table 1. Input parameters for the numerical modelling

Parameter	Value
Core diameter	12 μm
Cladding diameter (flat to flat)	130 μm
Core refractive index	1.4607
Cladding refractive index	1.4507
Coating refractive index	1.4027
Yb ³⁺ concentration (cca 20 000 mol ppm)	$4.54 \times 10^{26} \text{ m}^{-3}$
Pump wavelength	975 nm
Radial resolution (pixels)	128 x 128

3. RESULTS AND DISCUSSION

In this study we analyzed both the effect of different radii of the spool on which the fiber is coiled and different fiber twisting rates. Two different launching conditions were investigated: the Gaussian input pump beam and a speckle pattern that mimics the output of the pump laser diode pigtail with 105 μm core. The initial field of the two pump launching conditions can be seen in Fig. 2 on the left column of the pump field distributions. Due to squeezing of the pump field by fiber bending, as can be seen in the other pump field distributions in Fig. 2, the overlap of the pump with the core changes and correspondingly the overall absorption is varying, see Fig. 3(a). Therefore, the absorption trends are not monotonous with respect to bending radius because the particular input speckle pattern has different overlap with the absorbing core for different bending radii. Even relatively sharp excessively high peaks in absorption curves may appear as indicated in the detailed calculation window in Fig. 3(b). Since the pump beam is more squeezed to the edge of the fiber for smaller bending radii, the overall pump absorption may decrease with tighter coiling.

Significant squeezing of the pump field towards the edge of the fiber gives rise to the idea of enhancement of absorption by asymmetric positioning of the rare-earth doped core. It should be noted, that asymmetric positioning of the core was used already in other double-clad fiber designs. For example, Elias Snitzer anticipated higher overlap of the pump radiation with the doped core for asymmetric position of the core [Snitzer88], or the asymmetric position was found beneficial for easy coupling of the multimode pump fiber and the signal fiber onto a double-clad fiber with stadium-like cross section of the inner cladding [Peterka06]. To our knowledge, the effect of asymmetric position of the core in the hexagonal double clad fiber under realistic twist and bend condition has not been studied yet. Apart from central core position, four other different positions of the core were tested as depicted in Fig. 4(a). The corresponding pump absorption is shown in Fig. 4(b). Asymmetric position of the rare-earth-doped core can significantly improve the pump absorption. Absorption improvement of about 10 dB can be achieved for core positions more than 20 μm positioned apart from the fiber axis.

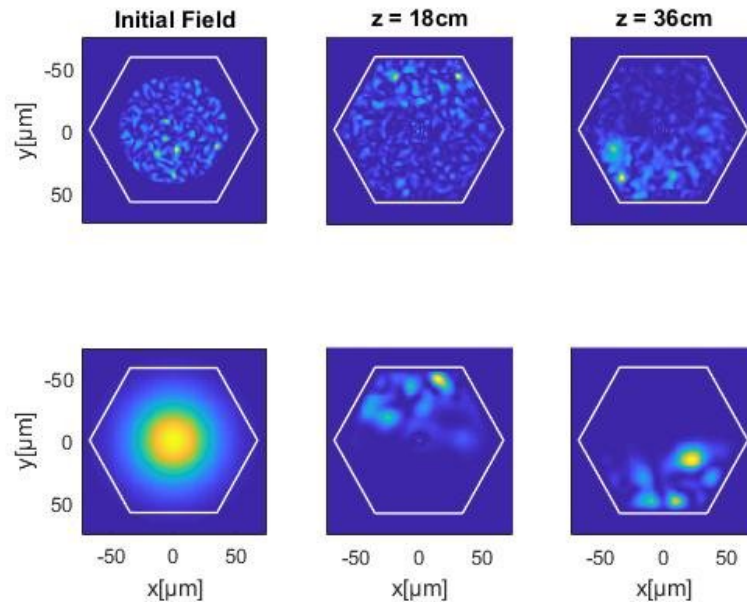
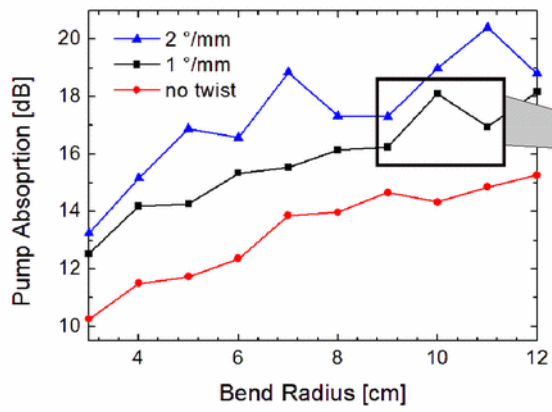
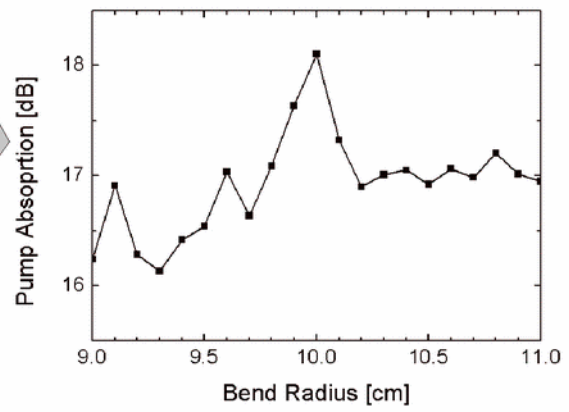


Figure 2. Pump field distribution at different positions along the hexagonal fiber with a central doped core. The top figures and bottom figures represent the speckle pattern and the Gaussian input pump field distribution, respectively. The twist rate is $1^\circ/\text{mm}$.



(a)



(b)

Figure 3. Absorption for different bending radii and twisting rates for the speckle pattern input. Part of the left figure is zoomed in the right graph. The fiber was 1 m long.

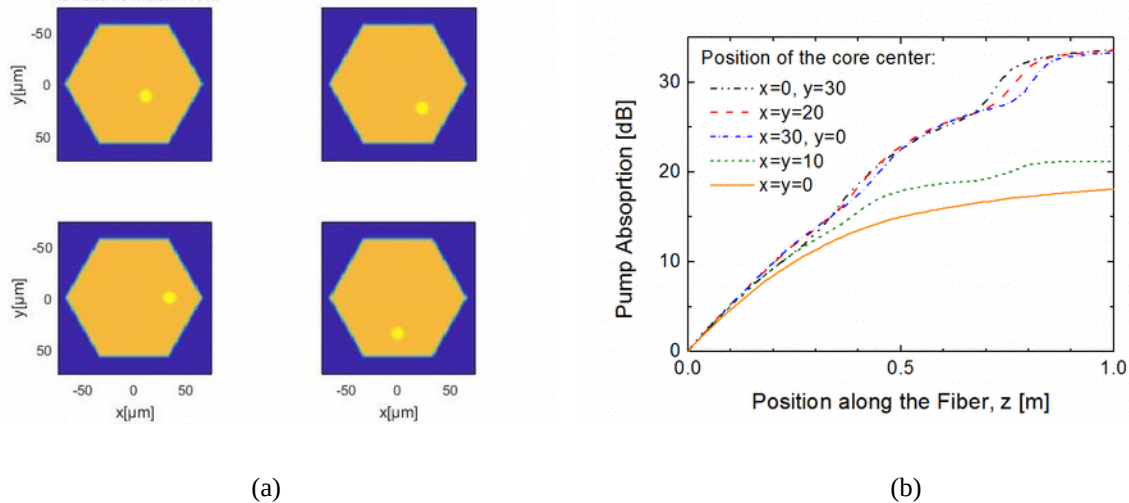


Figure 4. (a) Cross sections of the hexagonal fiber with a non-concentric core at different positions. (b) Evolution of the pump absorption along the propagation with a coiled and twisted double clad fiber for different position of the center of the core. The offset core leads to higher pump absorption.

4. CONCLUSIONS

We have shown the influence of the bending radius and the twisting rate on the absorption of the pump inside double clad hexagonal fiber. It was shown that simultaneous bending and twisting may result in significant raise up the absorption rate. While the twisting influences the rotation of the field around the center of the inner cladding, the bending radius affects the squeezing of the field around the edges of the cladding. The possibility of drawing fibers with such refractive index profiles (in particular with non-concentric core) offer great opportunities to obtain double-clad active optical fibers with high absorption rate.

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