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POWDER TECHNOLOGY AND INNOVATIVE FIBER DESIGN ENABLING A NEW GENERATION OF HIGH-POWER SINGLE-MODE-FIBER LASER SOURCES

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Powder technology and innovative fiber design enabling a new generation of high-power single-mode-fiber laser sources

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Abstract

By simultaneously providing ultra large mode effective area (ULMA) and close to diffraction limited laser beams, Yb-doped double-clad photonic crystal fibers have become key components for power scaling in fiber laser systems. Despite their advantages, such fibers suffer from some drawbacks among which tremendous fabrication complexity and arising costs, high bending losses and poor integrability. In this paper, we show how the REPUSIL technique, which is an alternate synthesis method to produce high-quality doped-silica, enables the design of a new generation of ULMA rare-earth-doped fibers. Some examples of innovative fiber designs will be shown and commented together with a first experimental demonstration of all-solid Yb-doped double-cladding fiber fabrication. The thermal effects, which play a major role at high power laser level and drastically compromise the single-mode regime, are also investigated. The very first experimental results for the fiber and laser characterization are given.

Introduction

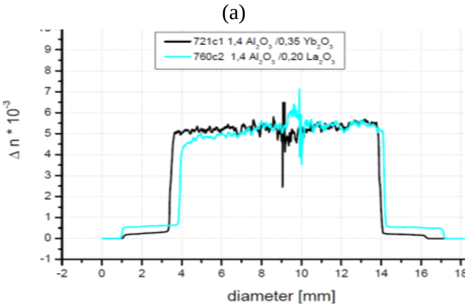
Rare-earth-doped fiber lasers and amplifiers constantly benefit the best of fiber technology demonstrating outstanding increase of output average and peak power [1]. Fiber lasers are currently replacing bulk solid-state lasers in numerous applications [2]. This accession was particularly marked in the last ten years with the development of laser sources based on photonic-crystal-rod-type fibers exhibiting very large effective areas with core diameters up to 100µm [3,4]. For future power scaling of fiber lasers and amplifiers, the required effective area enlargement can be detrimental for the beam quality as the core and cladding index control become more and more critical. This is even more critical since thermal effects have been clearly identified as being responsible for strong beam quality degradations during high power operation. Thermal loading, inducing a parabolic transversal thermal profile in the core [5] and thermally induced long-period gratings [6], are two plausible assumptions currently investigated. The extreme required precision on refractive index profile implies the use of complex manufacturing techniques that lead to exorbitant fabrication cost. Furthermore, the impact of thermal induced effects cannot be easily managed with current technology, a radical change in fabrication techniques would be a real breakthrough. In this paper, we aim to show that the REPUSIL technology makes possible the design and the development of low cost all-solid microstructured fibers for a next generation of fiber laser sources.

Suitable Material Synthesis and Properties

During past few years, the development of specific rare-earth doped Photonic Crystal Fibers (*i. e.* rod-type fibers [3,4] and Large Pitch Fiber [7,8] in particular) has led to a drastic increase of the mode field area while keeping a singlemode operation based on higher-order mode delocalization. Regarding the fabrication step of such ULMA fibers, the very good index homogeneity as well as an accurate control of the refractive index are simultaneously required for all material constituting the core and the cladding. The cladding of these fibers is composed of a regular array of air holes embedded in a pure silica matrix whereas the core is fabricated using an index compensated doped silica to ensure suitable singlemode propagation conditions. Thus the core material is a sub-wavelength arrangement of rare-earth-doped-silica and fluorine-doped silica rods (both fabricated by the well-known MCVD process) which require numerous delicate stack and draw operations resulting in a risky, expensive and time-consuming process.

An alternate method proposed here in order to overcome the previous drawbacks is the REPUSIL method. The latter is one of the newest glass manufacturing technologies which has already demonstrated very good capabilities for the fabrication of efficient and homogeneous active material. For instance, a multimode low-loss (background loss ~ 20 dB/km) Yb-doped fiber laser has been recently fabricated and exhibits excellent slope efficiency (~ 80%) with a measured signal output power larger than 1 kW [9]. By this technique, the material synthesis is performed in several steps. First, an aqueous solution of extremely pure silica particles is doped in a liquid phase with rare-earth precursor while being stirred at a constant speed to increase the homogeneity. Then, the solution is dehydrated and drained to get only the powders granulates and to suppress the entire water amount. Afterwards, the obtained powder (see figure 1.a) is mechanically compressed to get a cylinder shape, put into a silica tube and purified with chlorine at a high temperature to remove inorganic impurities and organic residues. Finally, the doped rod is sintered and vitrified on a MCVD lathe giving access to high quality doped materials (see figure 1.a). Figure 1.b shows a typical refractive index profile of such a vitrified doped-rod underlining the very small variation of the refractive index value through a cross-section (~ 4.10^{-4}). Obviously, the use of rare-earth doped powder-sinter material as core material enables a substantial simplification of the fabrication stage. To obtain more information about the glass fabrication process, please see references [9] and [10].

(a)



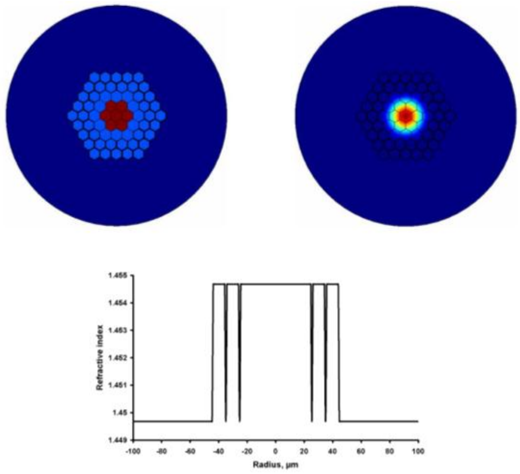
(b)

Figure 1: a) Yb-doped granulate produced by a suspension doping of synthetic SiO_2 particles and Yb-doped rods which are the basis for the production of laser active fibers. b) Measured refractive index of powder-sinter-material (the fluctuation in the middle of the preform is a numerical artefact).

The REPUSIL method ensures a supplementary degree to develop an all-solid ULMA fiber as the cladding can fit all requirements for singlemode operation if it is made of a judicious arrangement of passive index matching powder-sinter material and pure silica (see next section), whatever the core index value. Undoubtedly, an all-solid fiber structure avoids dust contamination, presents no obstacle for splice and reduces the thermal loading of the gain medium due to a highest thermal dissipation compared to air hole.

Smart Design and Modeling

We have investigated several all-solid ytterbium-doped fiber designs which can be easily fabricated by the REPUSIL process.



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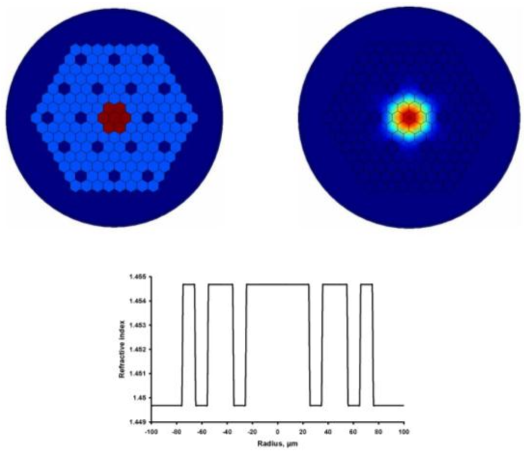
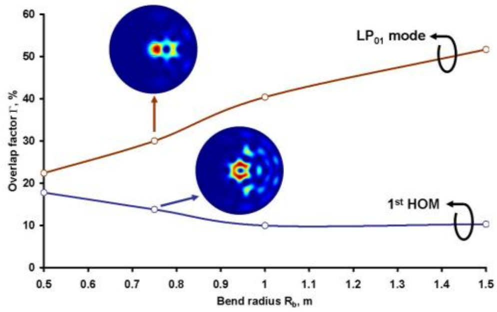


(b)

Figure 2: Schematic description of two proposed fiber designs: cross-section (dark blue area: pure silica, light blue area: high-index passively doped silica, red area: Yb-doped rods), computed intensity distribution of the fundamental mode and refractive index profile computed on x-axis for a) pure-silica-honeycomb in high refractive index material and b) large pitch fiber.

In each case, the proposed designs contain three different materials: i) the Yb-doped core material exhibiting a refractive index higher than that of pure silica (depending on the Yb concentration), ii) a high-index passively doped silica whose refractive index match exactly to the one of the doped core and iii) a pure silica material. Figure 2 shows two proposed designs: a pure silica honeycomb structure embedded in a high-index material (figure 2.a) and an all-solid Large Pitch Fiber (figure 2.b). Here, the core (50 µm in diameter) is composed of 19 high-index cells whose only 7 are doped with rare-earth ions (partial doping of 60%). In these both structures, the light guidance mechanism is based on a modified total internal reflection. The modal competition has been numerically studied using commercial software based on the finite element method. Despite a large core size of 50 µm which is by nature strongly multimode, a single-transverse-mode emission is ensured by the presence of the low-index pure silica inclusions (circular shape or rod shape) in the high-index doped silica matrix ensuring a higher-order mode delocalization.

Moreover, the increase of the mode field diameter in order to obtain singlemode ULMA fiber leads to increase the fiber bend sensitivity on one hand and to a distortion of the fundamental mode implying a reduction of the effective area of the guided mode in an other hand. By this way, we have also investigated the bend sensitivity of the proposed structures. Figure 3 compares the influence of a bend radius R_b on the overlap factor Γ of the guided core modes with the rare-earth doped core area for a conventional air/silica LPF structure (similar to that proposed in reference [7]) and the two proposed new designs. In each case, the evolution of the overlap factor Γ according to R_b is computed for the fundamental mode (LP_{01}) and the most confined high-order mode which can alter the singlemode behaviour of the fiber. Here the working wavelength is $\lambda = 1.06$ µm. Moreover, the three fiber structures exhibit a mode field diameter close to 50 µm. We observe that the proposed all-solid LPF fiber presents similar characteristics than the conventional air/silica LPF fiber, that is to say a drastic decrease of the overlap factor of the guided fundamental mode for $R_b < 1$ m. For such bend radius, the delocalization of the fundamental mode outside the actively doped core is not negligible and the fiber becomes multimode as higher order modes can be more localized in the gain area of the core. In opposite to this, the second proposed design based on a honeycomb structure appears more bend-resistive than the previous fibers. For bend radius as low as 30 cm, the distortion of the fundamental mode is less pronounced, inducing the conservation of the singlemode behavior of the structure with an overlap factor Γ close to 70%.



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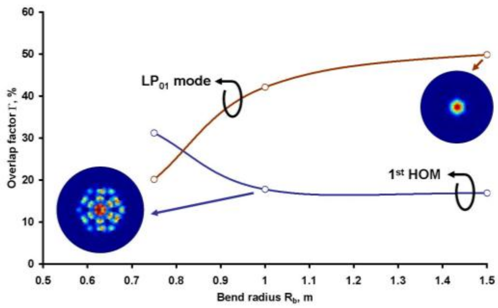

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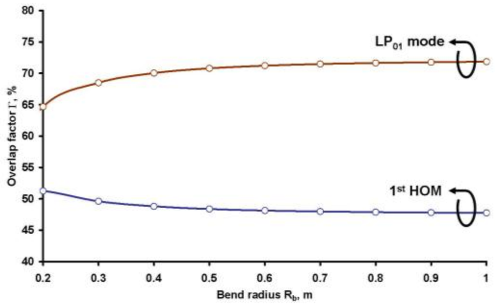


(c)

Figure 3: Computed overlap factor Γ between the rare-earth doped core area and two guided modes (fundamental mode: red curve; first high-order mode: blue curve) versus the bend radius R_b. a) conventional air/silica Large Pitch Fiber as proposed in [7], b) all-solid Large Pitch Fiber and c) all-solid honeycomb structure. Inset: computed near-field intensity patterns for the two modes.

Influence of thermal effects

Most of the time, thermal effects are neglected in active optical fibers as the large ratio between the transverse surface of the fiber and the active volume ensure an efficient natural cooling. However, this assumption has to be reconsidered for ULMA fibers and thus for very high power fiber lasers. Indeed, ULMA fibers are naturally multimodal fibers in which mode confinement is very weak. Numerous parasitic effects can therefore disturb the modal competition and the expected singlemode emission is often altered [11, 12]. For instance, for future developments in the kW range, thermal effects induce significant index changes which can alter dramatically the effective mode area of the guided core modes as well as the singlemode behavior of the fiber structure. By this way, theoretical investigation has to take into account the influence of thermally induced refractive index change on the guidance properties of the all-solid Large Pitch Fiber proposed above (see figure 2.b). Note that an all-solid structure confers a high thermal dissipation because of this mechanism relies only on heat conduction effect (in opposite to convection behavior in structures composed of air holes). Thus the fiber proposed here is expected to be less influenced by thermal loading compared to the conventional air/silica LPF structure.

A lot of publications deal with the theoretical description of thermal loading in optical fibers. In these works, step-index fibers with standard doping levels are commonly considered and the thermal properties (*i. e.* diffusivity, conductivity and expansion coefficients) of the different materials constituting the rare-earth doped core and the cladding are those of pure silica F300 material. However, to the best of our knowledge, nobody has considered composite fibers made of heterogeneous materials like ULMAs especially when the materials used are unusual (fabrication process, nature or concentration of dopants).

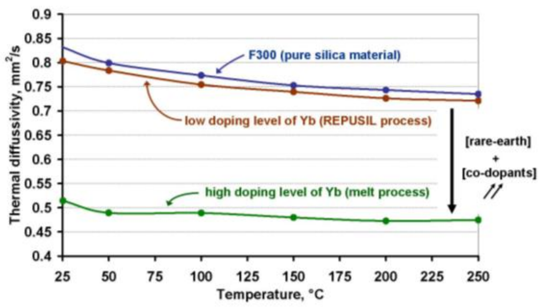


Figure 4: Measured thermal diffusivity for three different samples: a slice of pure silica F300 rod, a slice of low concentration Yb-doped material fabricated by the REPUSIL process and a slice of high concentration Yb-doped material fabricated by the melt process.

In order to secure our assumptions, we have measured the thermal coefficients of several materials which could be used as raw material for the fabrication of our fibers. Among ten samples, six have been fabricated by REPUSIL technique and are made of 98% silica and 2% of various concentrations of rare earth (Yb or Tm) and aluminum. Four other have been prepared by melt process [13] and are composed of 70% of silica and 20% of aluminum, 10% of La and Yb. Figure 4 shows the measured thermal diffusivities of only three samples, in order to clarify the figure. All 98% silica materials exhibit thermal diffusivities close to that of pure silica whereas that of the 70% silica materials are significantly decreased (~ 40%). So all proper thermal coefficients of each material have to be known to perform accurate modeling. Furthermore, F300 standard thermal values could only be used for standard level of doping and tailored values have to be considered for custom materials.

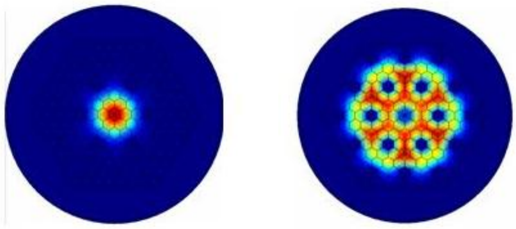
In the following, materials made of 98% of silica (pure silica, high-index doped silica and rare-earth doped silica) are considered, so standard values of F300 silica are used.

We have developed a model applied to a piece of fiber used in a laser cavity whose the pump is co-propagative. Moreover the cavity is composed of two dichroic mirrors around 1030nm: 4% of reflectivity in input and 99% in output. Here, we have considered a 1m-long piece of all-solid Large Pitch Fiber as shown in figure 2.b (Λ = 30 µm, $D_{outer\ cladding}$ = 200 µm, D_{core} = 50 µm, $D_{doped\ area}$ = 30 µm). Our model runs in four steps. First, the evolution of the emitted signal power P_S and the gain G are computed for different fixed pump power P_P. In a second time, the heat loading noted Q_0, induced on the active medium of the fiber, is computed as shown in reference [14]:

$$Q_0 = \frac{\lambda_S - \lambda_P}{\lambda_P} \times \frac{\sigma_e N_2 - \sigma_a N_1}{\pi r^2} \times \Delta P_S \qquad (1)$$

In the above equation, λ_S and λ_P are the pump and signal wavelength respectively, σ_e and σ_a, the signal emission and absorption cross section, N_2 and N_1, the ions concentration on the excited and fundamental state, and ΔP_s, the variation of signal power. Then, the thermally induced refractive index change is computed. Finally, the transverse mode competition in the laser is modeled taking into account new modal content and its impact on transverse population inversion [15]. The quality of output laser beam is then deduced from the power distribution carried by each transverse mode. In figure 5, we presented the computed intensity distribution for the two first guided modes under 100W (see figure 5a) and 2kW (see figure 5b) of pump power. Figure 5 clearly illustrate the fact that the first high order mode LP_{11} is well confined into the central gain area of the core and this can enable degradation of the emitted beam (modal instabilities, multimodal emission).

In Figure 6.a, at low pump power level (100W), 99.9% of the power is emitted on the fundamental mode. In figure 6.b, the thermal induced refractive index profile under 2kW of pump power relocalize the LP_{11} mode in the core and the emission becomes multimode as only 64.9% of the total power is carried by the fundamental mode.



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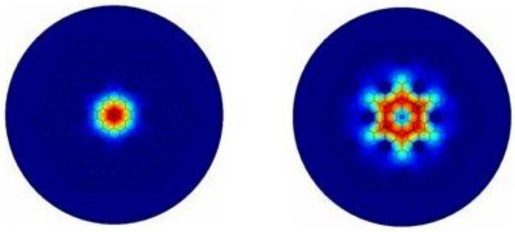
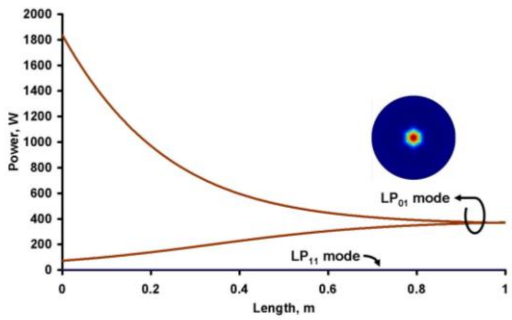


(b)

Figure 5: Computed near-field intensity patterns for the two modes. Electric field repartition on All Solid LPF: a) with initial refractive index profile and b) under 2kW.



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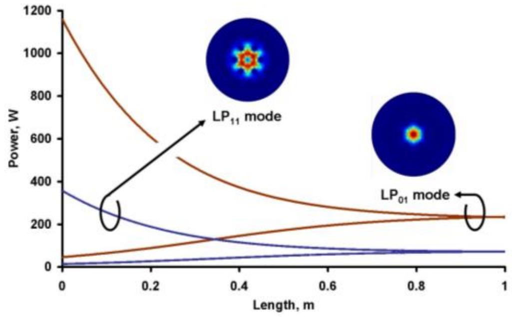

(b)

Figure 6: Evolution of the computed signal power along the all-solid LPF fiber for the two first guided modes (LP_{01} and LP_{11}): a) for low pump power level ~ 100W and b) for high pump power ~ 2 kW In inset: computed near-field intensity patterns.

Conclusion

Taking benefits from the opportunities offered by REPUSIL method, an alternate way to synthesize passive or active doped-silica, we propose here new all-solid ULMA rare-earth-doped-double-clad-fibers designs for the next generation of fiber laser sources. For high power lasers, thermal heating of materials strongly impact the refractive indices of fiber materials and the impact on laser transverse modal population is studied. Through one realistic example of fiber laser, the evolution from singlemode to multimode emission with an increase of pump power is calculated.

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