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Large Mode Area All-Solid Optical Fiber Lasers with Tailored Microstructured Cladding

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Abstract *Improvements, in terms of output power, spatial beam quality, bend insensitivity … are still required in the field of single-mode fiber lasers. A major trend is to increase the active core area to increase the thresholds of nonlinear effects while ensuring a transverse single-mode behavior. Actually, increasing the active ions' concentration is also demanded since it allows a drastic reduction of the fiber length, everything being equal. Two non-exclusive strategies are laid out to overcome fiber laser limitations. On the one hand, a large mode area photonic bandgap fiber is shown to lead to a transverse single-mode fiber laser with very good lasing efficiency. On the other hand, it is demonstrated that surrounding a highly multimode active core by a properly designed microstructured cladding allows the fiber laser to be operated in the single-mode regime.*

Keywords fiber lasers, microstructured cladding, photonic bandgap effect

1. Introduction

Nowadays, fiber lasers are entering the market of high-power lasers [1]. Nonlinear effects (mainly stimulated scatterings), whose threshold is conversely proportional to effective mode area (A_{eff}) and proportional to fiber length, are main limiting factors leading to significant disturbance of spectral and spatial properties of the output beam. High-power generation requires large mode area (LMA) fibers to increase the threshold of optical nonlinearities while preserving a single-mode emission. The LMA architecture is usually obtained at the cost of a weakened guidance, leading to high bend-sensitivity. Hence, the fiber must be straight to avoid any power leakage, forbidding the construction of

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compact fiber lasers. Moreover, bending-induced mode distortion seems a critical issue to tackle [2].

Solutions based on effective single-mode fibers were recently proposed. Here, multimode fibers are used and modal filtering is carried out. Filtering techniques imply a spreading of the modal field from the active area, favoring emission of a single mode, usually the fundamental mode. Together with the discrimination of high-order modes by proper curvature of a highly-multimode fiber [3], the use of helical-core fiber [4], spun-double-core fiber [5], or gain-guided, index-anti-guided fibers [6] are promising techniques.

On the other hand, nonlinear thresholds may be increased by decreasing the fiber length. Everything being equal, this could be done by increasing the active ion concentration. Despite the use of fluorine ion, rare-earth ion, and aluminium ion co-doping increases the refractive index of the core material. Hence, the average rare-earth ion concentration in the core must be kept low to ensure a low numerical aperture. Strategies must be deployed to simultaneously obtain high active ion concentration and single-modedness.

In this communication, our endeavors toward high-power fiber laser construction under the above mentioned constraints are reviewed. Attention was paid to appropriate fiber designs. In section 2, all-solid photonic bandgap fiber is shown to be promising for high-power fiber lasers. In section 3, strong interaction between a highly multimode core and a properly tailored microstructured cladding is shown to lead to effectively single-mode operation of a fiber laser.

2. Photonic Bandgap Fiber Laser

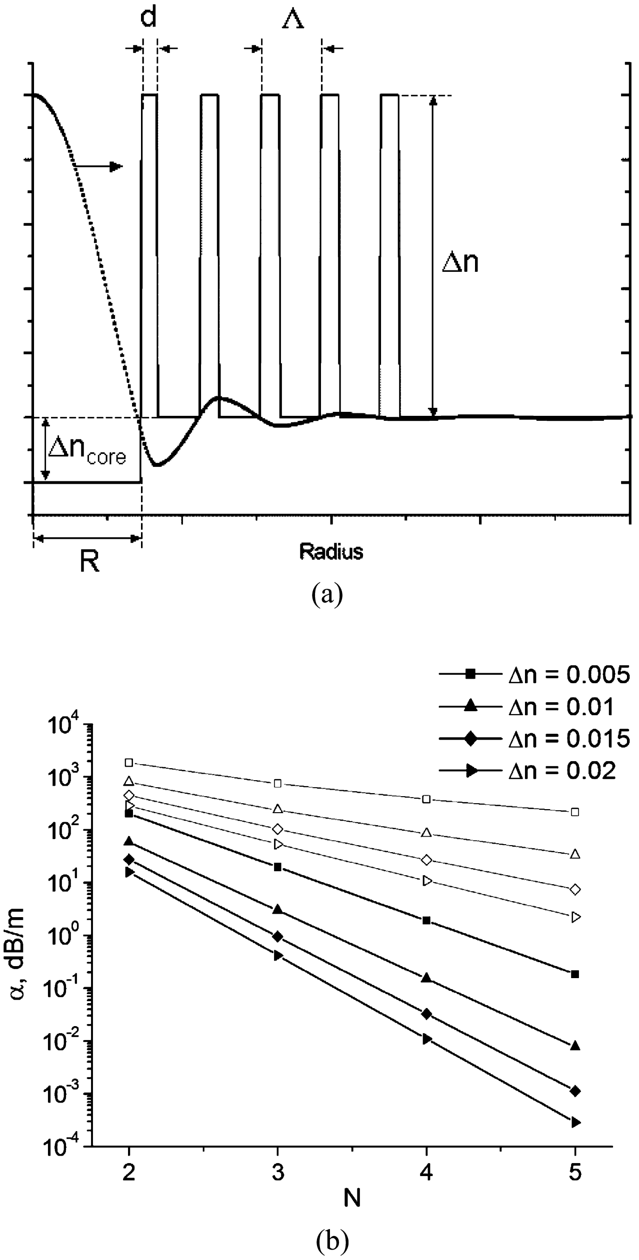
We have recently proposed to simultaneously address single-modedness and bend loss issues by implementing a LMA photonic bandgap fiber (PBGF) [7].

A PBGF is basically composed of a low-index core surrounded by a periodic cladding. In certain circumstances, light can be reflected off the cladding inclusions and efficiently guided in the core even in absence of total-internal reflection. The photonic crystal can be designed to efficiently guide one core mode, leading to single-mode operation. Moreover, this mode can be tightly trapped to the core even if the fiber is bent. Modal discrimination and resistance against curvature can then be obtained in PBGF. Such a fiber then becomes a convenient platform for high-power delivery or generation.

Design rules towards an Yb^{3+}-doped LMA bend-resistant PBGF are examined. Experimental results concerning the continuous wave (cw) and pulsed operation regimes are given. Conclusions and prospects about the fiber design are drawn.

2.1. Design Rules

The canonical form of the refractive index profile of the PBGF studied is shown in Figure 1a. The perfectly circular fiber consists in a low-n core surrounded by an alternation of high- and low-n layers constituting a cylindrical Bragg mirror [7, 8]. As shown in Figure 1a, the electric field amplitude of the fundamental mode is mainly located in the core. Exponentially decaying oscillations in the cladding come from the PBG effect and are related to antiresonance of the high-n layers. The oscillating field outside the periodic cladding implies confinement loss. The goal of the design stage is to optimize the index profile so that a modal discrimination occurs thanks to differential modal confinement loss.



(a)

(b)

Figure 1. (a) Index profile and electric field amplitude of a cylindrical PBGF. (b) Confinement loss computed for LP_{01} (filled signs) and LP_{11} (hollow signs) for $R = 10\ \mu m$.

The design parameters are the core diameter $2R$, the core index contrast Δn_{core}, the cladding index contrast Δn, the high-n layers' thickness d, the period Λ of the cladding and the number N of high-n layers. The core parameters (R, Δn_{core}) determine the modal propagation constant in the core. The periodic cladding must then be optimised for efficient reflection of this peculiar mode. This dictates d and Λ. It was shown that a

$\Delta n_{core} = 0$ allows a better modal discrimination. Thus, once the core diameter is fixed (e.g., $R > 10$ μm for LMA operation at $\lambda = 1$ μm), design space reduces to $\{\Delta n, N\}$. Figure 1b plots the confinement loss for LP_{01} and LP_{11} modes as a function of N for various Δn when the fiber core is 20-μm in diameter. For $N = 3$ and $\Delta n = 0.015$, a very large mode discrimination is obtained, leading to an asymptotically single-mode fiber. These parameters were used to fabricate a fiber.

2.2. Experimental Results

The fiber was fabricated at the ICHPS and FORC. The refractive index profile of the fiber is shown in Figure 2a. The core is highly Yb^{3+}-doped with 10,000 ppm by weight.

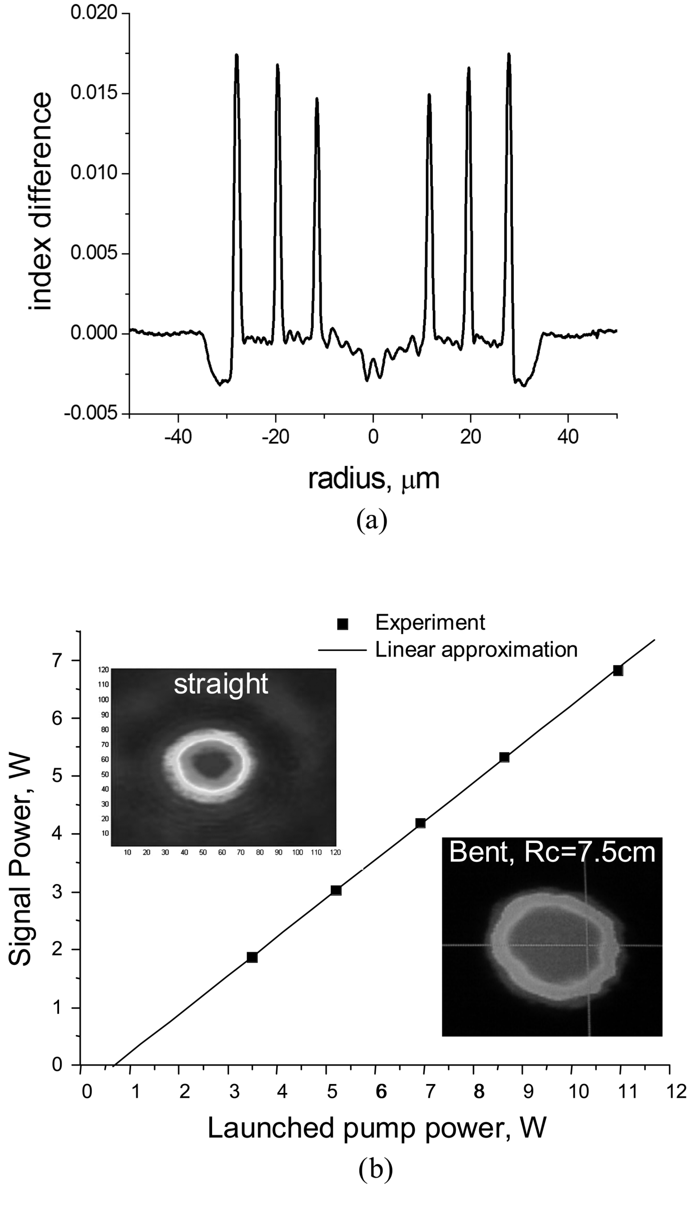
2.3. Continuous Wave Regime

The fiber was inserted in a laser cavity and the fiber laser was operated in cw regime [9]. Figure 2b shows the emitted power versus the launched pump power together with the emitted beam. The slope efficiency measured versus the absorbed pump power reaches 84%, a value similar to the state of the art. As shown in inset, the fiber is single-mode either when it is straight or wound onto a 7.5-cm radius reel.

2.4. Pulsed Regime

Mode-locked single-mode rare-earth-doped fiber lasers are nowadays routinely operated and are entering the market to address real world applications. However, peak power and pulse energy scaling of mode-locked fiber lasers is not as straightforward as in their bulky counterparts. Nonlinear effects avoid self-consistent pulse evolution inside a fiber laser resonator and hinder the pursuit of higher pulse energies. We realized a mode-locked fiber laser based on the LMA bandgap fiber. The second order group velocity dispersion of the fiber was estimated to be about 0.019 ps^2/m. The laser cavity is mounted in a sigma configuration by using a polarization-sensitive optical isolator. Passive mode-locking is achieved using a fast SEmiconductor Saturable Absorber Mirror (SESAM) introduced in the sigma branch. Mode-locking is obtained by optimizing the saturation criteria on the saturable absorber, using an adequate focusing lens. The total cavity length is about 4.3 m, resulting in a repetition rate of 58 MHz. In this configuration, the laser started in a Q-switched mode-locking state at an average power of 100 mW. By increasing the pump power, stable mode locking was obtained at an output average power of 220 mW. Figure 3a shows the typical optical spectrum obtained for an output average power of 232 mW, which corresponds to energy per pulse of 4 nJ. The autocorrelation measurements show that the pulse duration is 3.5 ps, assuming a Gaussian pulse shape (Figure 3b). The output pulses are extra-cavity dechirped to 1.3 ps duration by using bulk gratings (see inset in Figure 3b). The time-bandwidth product is about 0.72. It is 1.6 times higher than the Fourier-transform limit. This indicates that the output pulses suffer from an amount of nonlinear chirp. By increasing pump power, the mode-locking regime remains stable for output average powers higher than 350 mW (6 nJ). These preliminary results show that ytterbium-doped large-mode-area bandgap fibers present real potentialities for energy scaling in mode-locked fiber lasers.

The output power could be increased by enhancing the angle cleaving of the output end facet.



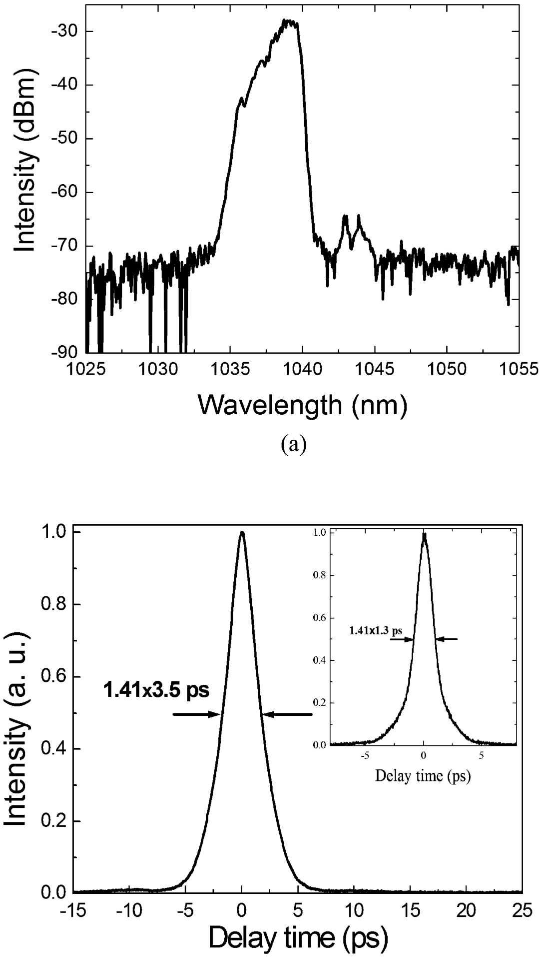
(a)

(b)

Figure 2. (a) Index profile of fabricated Yb^{3+}-doped PBGF. (b) Output power as a function of the launched pump power for the straight fiber. Inset: Beam profile observed at the output end of the straight and wound fiber.

2.5. Conclusions and Prospects

High-power bandgap fiber laser was operated in the cw regime. A peculiar feature of this fiber architecture is the relative bend insensitivity. A mode-locked fiber laser was also constructed, exhibiting ps pulses with few nJ energy, only limited by technical issues. Upscaling of the output power may be reached by modifying the fiber design. Design



(a)

(b)

Figure 3. (a) Typical output optical spectrum. (b) Autocorrelation trace of the output pulses. Inset: Autocorrelation trace of the dechirped pulse.

rules show that a 50-μm core fiber can be designed to operate in the single-mode regime. Other attracting features of the PBGF such as self-spectral filtering could be used in fiber lasers (lasing at short wavelength or stimulated-Raman-scattering suppression).

3. Fiber with Large and Highly Rare Earth Doped Core and Resonant Cladding

As mentioned above, nonlinear impairments can be drastically reduced by shortening the laser medium. For a given output power level, the higher the rare earth ion concentration, the shorter the fiber length. On the other hand, for a given length of fiber, the higher the rare earth ion concentration, the higher the output power level. However, increasing the rare earth concentration is obtained at the cost of a high aluminium content, i.e., a higher core index contrast and thus a larger number of modes. In order to relax the constraints applied on the rare earth concentration, we propose to tailor the refractive index profile of a microstructured cladding.

3.1. Design Examples

The canonical form of the transverse index profile is shown in Figure 4a whereas a detailed radial index profile is shown in Figure 4b. The fiber is composed of a highly multimode core (diameter $2R$, index contrast Δn_{core}) surrounded by a periodic cladding composed of a two-dimensional array of high-n rods (diameter d, maximum index contrast Δn, number of layers N). The high-n rods may exhibit either a parabolic- or a step-index-like index profile. A core diameter as large as possible is sought for. For instance, $2R = 25$ μm is a reasonable value for a LMA fiber laser operated at 1-μm wavelength. Moreover, $\Delta n_{core} = 10^{-2}$ authorizes an Yb^{3+} concentration as high as 4 wt % (40,000 ppm-wt).

Such a core, when surrounded by homogeneous pure-silica cladding, supports a very large number of modes. However, a properly designed cladding can support modes likely to couple to core modes at various phase-matching wavelengths. In such a case, some core modes spread out the core. Thus, the overlap factor between the considered mode and the gain medium drastically decreases leading to a poor amplification of the mode. On the other hand, an uncoupled core mode, e.g., the fundamental one, can be tightly

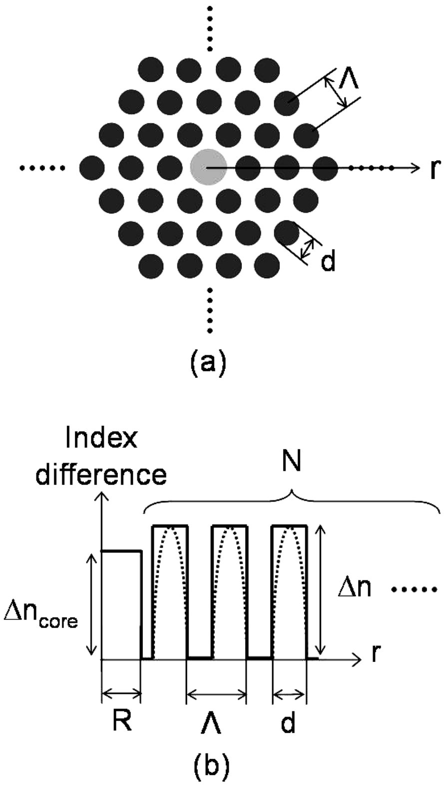
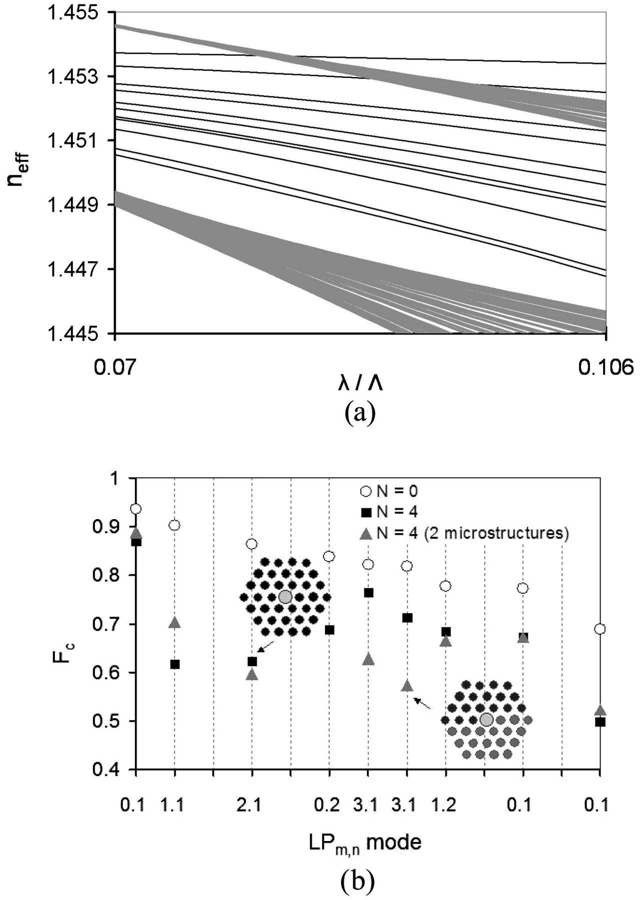


Figure 4. Schematic representation of the transverse section of the fiber with large and highly rare-earth doped core and resonant cladding. (b) Radial index profile along the direction $\phi = 0$.

confined in the core and efficiently amplified. Finally, such a fiber can allow amplification of a single mode. According to coupled mode theory, both phase matching and overlap factor between coupled modes must be considered. The effective index (n_{eff}) curves of various core modes and of various cladding modes have been computed versus the normalized wavelength (λ/Λ) and plotted in Figure 5a. Due to the periodic nature of the cladding, cladding modes gathers into bands. At specific wavelengths where core and cladding modes have the same effective index, phase-matching conditions are fulfilled. As shown in Figure 5a, phase-matching conditions cannot be fulfilled for all core modes simultaneously. On the other hand, for a core mode to be coupled to the cladding modes, overlap integral must be non-zero. The fraction of electric field in the core (F_c) has been computed and plotted in Figure 5b for the first nine modes of the isolated core ($N = 0$). The modal confinement and thus F_c decreases with increasing mode order. Consequently, overlap integrals are non-zero even in absence of phase matching. Hence,



(a)

(b)

Figure 5. Theoretical results related to the fiber with core: $2R = 25\ \mu$m, $\Delta n_{core} = 10^{-2}$, parabolic rods: $\Delta n = 16\ 10^{-3}$, $d = 20\ \mu$m, $\Lambda = 22\ \mu$m. (a) Effective index curves of core modes (black) and cladding modes (grey). (b) Overlap factor versus the mode order for the core surrounded by pure silica ($N = 0$) and by 4 layers of inclusions ($N = 4$). Results obtained with a heterostructure in the cladding are also shown.

far from the phase matching, efficient coupling of higher order modes of the core to the cladding modes can occur. This is exemplified in Figure 5b for four cladding layers made of graded index inclusions (black squares, $\Delta n = 16\ 10^{-3}$) where it is shown that F_c is lower than 75% for all core modes but the fundamental one (87%) whereas, without the tailored cladding, eight high-order core modes exhibit $F_c > 75\%$.

The fifth core mode ($LP_{3,1}$), located in between the cladding bands, is the least affected and is likely to be emitted in the laser configuration. To overcome this problem, design improvement can be brought. In order to bridge the gap between bands, cladding can be divided in two different microstructures composed of two different kinds of inclusions. The band diagram of the second microstructure is slightly different from that of the first one, leading to a broader set of cladding modes. Consequently, slightly coupled modes in the first configuration become strongly coupled and F_c drops down to 70% for all high-order core modes as shown in Figure 5b (grey triangles).

From a practical point of view, such a complex structure must be fabricated using the stack and draw technique. The rare earth doped rod is extracted from a MCVD preform with diameter smaller than 2 mm. For a seven missing rod core, such a rare earth doped rod should be stacked with high refractive index rods smaller than 700 μm in diameter that greatly complicates the process of stacking and accurately maintaining the rods. A second design has been proposed to facilitate the manufacturing process based on a single missing rod. The optimized fiber was fabricated and fully characterized.

3.2. Experimental Results

An optimized fiber was fabricated upon the theoretical considerations and the opto-geometrical parameters of existing preforms. Parameters of the Yb^{3+}-doped core are $2R = 25\ \mu m$, $\Delta n_{core} = 5.5\ 10^{-3}$, $[Yb^{3+}] = 2{,}500$ ppm-wt. The core surrounded by pure silica should propagate 13 modes. For the high-order modes to spread out from the core, a 2-layer periodic cladding of graded index rods ($\Delta n = 17.5\ 10^{-3}$) was optimized. Modal overlap factors were computed for various inclusions' diameters and center-to-center spacings. Opto-geometrical parameters of the cladding are $d = 20\ \mu m$, $\Lambda = 22\ \mu m$. The fiber was then fabricated by the stack and draw technique. An optical microscope image of the cross-section is shown in Figure 6a. The core and surrounding rods exhibit hexagonal shape due to the expected deformations occurring during the drawing process.

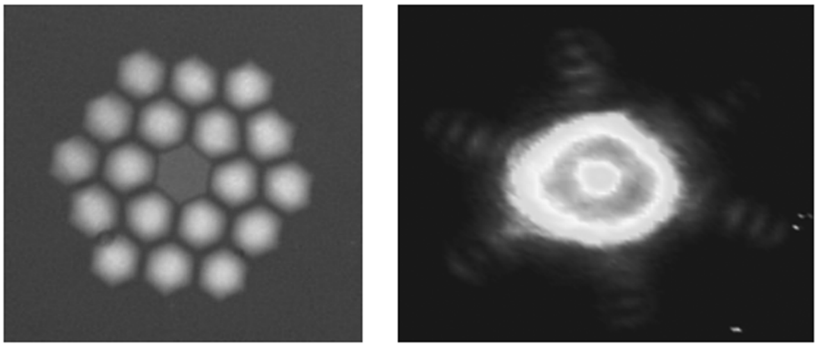

(a) (b)

Figure 6. (a) Optical microscope image of the cross section of the fabricated fiber. (b) Transverse intensity distribution of the output laser beam.

The 390 μm outer diameter fiber has a circular shape, not suitable for highly efficient cladding pumping. However, this does not impact on the modal filtering. A 4.5 W pump beam was launched into the cladding of a 1.35 m long sample of fiber and the optical feedback was operated by the cleaved end faces of the fiber. As shown in Figure 6b, the robust single mode emission is obtained although the laser mode is a second-order mode (TE_{01}). Indeed, within the gain region of ytterbium, this mode propagates with lower loss than the fundamental mode. Despite the fact that the effective indices are not very sensitive to the shape of the rods, the hexagonal shape is expected to be responsible for a slight shift of phase matching conditions, favoring the TE_{01} mode. For the emission of the single fundamental mode, a shift of coupling properties can be simply achieved by drawing the fiber with a suitable outer diameter that must be determined by accurate computations taking into account the actual cross section of the fiber. Such samples of fiber must be drawn to fully demonstrate the interest of the proposed fiber design for high quality high power laser beam emission.

3.3. Conclusions and Prospects

The emission of a single mode from a highly multimode core was experimentally demonstrated in the continuous wave laser regime. The theoretical principle underlying the modal filtering effect is based on the interaction between the multimode core and a tailored cladding composed of high-index rods. High order modes of the rare earth doped core spread out of the core and gain competition during laser operation leads to the suppression of all modes exhibiting a small overlap with the gain medium.

The experimental results demonstrate the feasibility of such a complex structure but it must be improved to reach high power level of emitted power. On the one hand, the ytterbium concentration must be increased to 4 wt% or more. On the other hand, emission of fundamental mode has to be achieved to fully demonstrate the concept.

Conclusions

In conclusion, two strategies to overcome limitations of fiber lasers in terms of output power and beam quality were proposed. Both strategies require a thorough optimization of fiber periodic cladding to suppress unwanted high-order modes. On the one hand, a photonic bandgap fiber was successfully fabricated. A LP_{01}-single-mode fiber laser was built in the cw and pulsed regimes. On the other hand, a two-dimensional periodic cladding was shown to efficiently couple high-order modes from the core to the cladding, leading to an efficient modal discrimination by the gain. A LP_{11}-single-mode fiber laser was built in the cw regime.

Acknowledgments

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Biographies

Philippe Roy was born in May 1971 in Bellac (France) and received his Ph.D in Microwave Electronics and Optoelectronics (speciality Photonics and Electronics Systems) in 1997 at the University of Limoges. He is now a Researcher at XLIM, which is a mixed laboratory of the University of LIMOGES and CNRS. He is involved in the fabrication and characterization of composite fibers such as air-silica microstructured optical fibers (broadband chromatic dispersion, modal analysis, birefringence, cut off wavelength, and gain analysis). He develops rare-earth doped fiber with complex structure for high power fiber laser or nonconventional emitted spectrum.

Sébastien Février was born in 1976 in Périgueux, France. He earned his Ph.D thesis in 2002. Since 2003 he has been a lecturer at the University of Limoges, France and belongs to the Xlim Research Institute. He was engaged in research and development of optical fibers in the fields of fiber amplifiers, gain flattening filters, and dispersion compensating fibers. His research activities currently cover hollow and all-solid bandgap fibers for high-power generation or delivery and management of nonlinear effects and dispersion properties.

Laure Lavoute was born in Limoges, France, on May 14, 1981. She received her Ph.D degree in December 2007 from the University of Limoges, France. Currently, she has a post-doctoral position in the Photonic department of the research institute Xlim. In 2004, she has been engaged in research mainly on optical fibers. Her main areas of activity involve theory, design and experimental investigation on new Large Mode Area fibers based on original interaction between multimode core and resonance cladding for single mode emission.

Dmitry A. Gaponov was born in Liethuania (USSR) in 1982. In 2005 he graduated chair of laser physics in Advanced Physics Faculty of Russian Academy of Sciences in the Moscow Engineering Physics Institute (State University). He then became a post-graduate student of the Fiber Optics Research Center at the General Physics Institute of the Russian Academy of Sciences (FORC RAS). Here his speciality is, in general, laser physics. During his study at FORC RAS, a collaboration with the XLIM laboratory of the University of Limoges (France) began. He became a Ph.D student of both universities. A theoretical part of his work is related with the theory of novel types of fibers—microstructured optical fibers (in particular, with all-solid 1-D and 2-D photonic bandgap fibers). Currently, the experimental part of his work is related to high power fiber lasers based on large mode area photonic bandgap fibers. Up to the moment he has eleven published works.

Raphael Jamier received his Ph.D degree from the University of Limoges on “Linear properties of solid-core photonic bandgap fibers” in September 2007. Since October 2007, he has a post-doctoral position in the Photonic department of the research Institute Xlim. He has been engaged in research mainly on optical fibers. His main areas of activity involve theory, design and experimental investigation on photonic bandgap guidance fiber with solid core.

Caroline Lecaplain was born in Le Chesnay, France, in December 1984. She received her Masters degree in Optics from the University of Rouen, France in 2007. Currently, she is preparing her Ph.D degree at the Optics and Optonics Group of the CORIA Laboratory, University of Rouen. Her current research interests include high-power fiber lasers and ultrashort pulse generation and characterization.

Gilles Martel received his French M.Sc degree (DEA) in optical sciences in 1992. In parallel he is a graduated “engineer” from ENSSAT from Lannion (22, France) in the area of Optoelectronics. After spending one year (1993) in the department of “New Laser Sources” from Aerospatiale Industry where his research involved a modelization of optical nonlinear processes in birefringent materials. He received his Ph.D degree from Rouen University, France in 1996 on photorefractive nonlinear optics and physics of II-VI semiconductors applied in phase conjugated mirrors. This research was carried on at CNET research center from France Telecom. He has performed research in the area of microchip lasers, transverse mode diffraction, and more recently fiber lasers to optimize both their efficiency and temporal regimes (Q-switch and mode-lock). His research is also involved in the area of new generation of saturable absorbers such as carbon nanotubes or optimized SESAM for fiber lasers and part of it also involves modelization of ultra-short pulse propagation in nonlinear optical media.

Ammar Hideur was born in Tizi-Ouzou, Algeria, on February 7, 1972. He is Engineer in Electronics from the Mouloud Mammeri University (Algeria). He received his Ph.D degree in physics in 2001 at Rouen University on the study and realization of high-power fiber lasers. Since 2003, he has been assistant professor in physics at the University of Rouen. His research interests include high-power fiber lasers in the pulsed and continuous-wave regime, nonlinear optics, and laser metrology.

Mikhail E. Likhachev was born in the Moscow region of Russia in 1979. He received his B.S. and M.S. degrees in physical engineering from the Moscow Institute of Physics and Technology in 1999 and 2001, respectively. He joined the Fiber Optics Research Center of Russian Academy of Sciences in 1999. In 2005 he earned his Ph.D and his research position in FORC and is now Senior Research Fellow. His research activities are connected with fabrication and investigation of new types of special fibers: Bragg fibers, fibers doped with rare earth, highly Ge-doped and P-doped fibers, and more.

Kay Schuster has been engaged for many years in the preparation of specialty fibers based on heavy metal oxide glasses, chalcogenide glasses and high purity silica. His activities included the preparative operations of glass manufacturing as well as material characterization (DTA, TG, UV-VIS, FTIR spectroscopy, and refractive index) and fiber fabrication (preform and crucible drawing). Based on his knowledge and experience of both, special glass preparation and optical fiber drawing could be highly qualified at IPHT for different applications. Results of these activities were active non-silica single mode fibers for amplification (Pr^{3+} doped chalcogenide fibers for 1.3 μm and Er^{3+} doped HMO fibers for 1.5 μm broadband amplification). The recent activities of Dr. Schuster are concentrated on the design and preparation of special functionalized microstructured fibers (also called photonic crystal fibers) for passive, active and remote sensing applications. Very complex structures of these high silica-based fibers have been realized. In the applicative critical field of special sensor fibers for high temperature applications, Dr. Schuster is intensively engaged in the application and alignment of suitable fiber coating materials (ORMORCERs, siloxanes, and polyimide).

Jens Kobelke was born on February 2, 1959 in Merseburg. He studied chemistry at Technische Hochschule "Carl Schorlemmer" Merseburg (1979–1984) where he received his Ph.D in heterogenous catalysis in 1986. Since this time he works at IPHT Jena on development and preparation of special optical fibers based on different glass materials (e.g. chalcogenide glasses, HMO glasses, and high silica).

Stephan Grimm is a chemist and specializes in the field of glass chemistry and solid state chemistry. Since 1995 he has worked in the field of specialty optical fiber produced by the MCVD-Process, e.g., photosensitive germanium doped silica materials for Bragg grating inscription during the fiber draw process. He is an expert in the investigation of low- and high-pressure hydrogen interaction with pure and doped silica for photosensitization of fiber Bragg gratings and also for damage prevention in the UV-range. Furthermore, he has considerable knowledge in the FHD-process for the optimization of pure and doped silica in planar wave guide and in OH-optimization of silica glass for lithography applications in the industrial level. He is currently engaged in the preparation of Rare Earth doped laser fiber materials with new routes in manufacturing. He is significantly involved in the development of a new powder sinter process for the bulk production of doped silica glass for side pumped fiber lasers, microstructure fiber, LMA-type fiber, and rod-type fiber. Furthermore, he is engaged in the melt preparation of high silica glasses for nonlinear application.