Optimization of Nd-Doped LMA Fibers for High-Power Laser Emission Near 915 nm

Raphaël Florentin, Kilian Le Corre, Thierry Robin, Alexandre Barnini, Roopa Prakash, Giorgio Santarelli, Hervé Gilles, Sylvain Girard, and Mathieu Laroche

***Abstract*—We report on the development of low numerical aperture (NA) Nd-doped large mode area (LMA) fibers with optimized core/clad geometry to achieve high-power laser emission near 915 nm while maintaining near diffraction-limited output beam. The influence of clad-to-core ratio on the detrimental amplified spontaneous emission (ASE) at 1050 nm and on the beam quality was studied experimentally in different amplifier configurations. We also show that bending the Nd-doped LMA fiber to a precise radius of curvature significantly improves the overall laser performances of these fibers by limiting both higher-order modes and spurious ASE at 1050 nm. The possibility of all-fiber multi-stages amplifier configurations with diffraction-limited output beam is finally discussed.**

***Index Terms*—Optical fibers amplifiers, Nd-doped fibers, LMA fiber amplifiers.**

I. Introduction

THERE is still a great deal of interest for the development of high-power compact laser sources emitting in the near infrared (IR) spectral domain between 900 nm and 980 nm. Such laser sources can be used for core-pumping of Ytterbium-doped short fiber oscillators and amplifiers [1], [2], [3] or for specific applications in biomedicine such as two-photon microscopy [4]. These laser sources can also give access to pure blue or blue/green wavelengths between 450 nm and 500 nm after second harmonic generation (SHG) [5], [6], replacing bulky and inefficient Argon ion laser. The 3-levels laser transition $^2F_{5/2}\rightarrow^2F_{7/2}$ of the Yb^{3+} ion has already proved to be very efficient for the generation of short IR wavelengths near 980 nm. In 2008, specific fiber laser technology based on Large Mode Area (LMA) rod type photonic crystal fiber achieved 94 W near 980 nm with a good beam quality [7], [8]. More recently, an Yb-doped double-clad photonic bandgap fiber has resulted in 151 W at 978 nm with an excellent beam quality ($M^2 = 1.2$) [9].

The 3-level optical transition $^4F_{3/2} \rightarrow {}^4I_{9/2}$ of Neodymium-doped silica fiber has also a strong potential to generate even shorter IR wavelengths between 880 and 930 nm [10]. However, efficient laser emission based on the 3-level transition of Nd ions is quite challenging due to the strong competition with the 4-level transition $^4F_{3/2}\rightarrow^4I_{11/2}$ emitting near 1050 nm. Several methods have been investigated to overcome this spurious amplified spontaneous emission (ASE) near 1050 nm in Nd-doped fibers. The use of a specific W-type refractive index profile introducing a finite cut-off wavelength below 1050 nm has resulted in several hundred of mW near 910 nm from a cladding pumped Nd-doped fibers (NDF) [11], [12]. However, this fiber design is based on a small core diameter (<5 μm), which strongly limits the maximum output power in single-frequency or pulsed regime [13]. Power scaling to a few tens of watts was achieved using large mode area fibers with either a low clad-to-core diameter ratio to limit the gain near 1050 nm [14], [15] or a Photonic Crystal Fiber structure inducing distributed spectral filtering [16]. To date, the record output power from a Nd-doped LMA fiber laser is 113 W near 900 nm with a M^2 of 3.1 [17] whereas 81 W with a much better beam quality (M = 1.5) can also be mentioned [18]. A Nd-doped polarization-maintaining (PM)-LMA fiber with a core diameter of 30 μm and a cladding diameter of 125 μm has also been successfully used as a power amplifier stage in a master oscillator-power amplifier (MOPA), allowing to obtain 28 W of average output power [19] in sub-nanosecond pulsed regime. However, in spite of the very low core NA of 0.045, this fiber is slightly multimode at 915 nm. It therefore required precise free-space injection of the LP01 mode of the LMA fiber to maintain a good output beam quality ($M^2 = 1.25$) [19], which is not suitable for industrial integration.

In the current article, we present a study combining analytical, experimental and numerical investigations to determine the most suitable LMA-NDF geometry for high-power operation in an all-fiber configuration while maintaining near-diffraction limited beam. In all previous reports on LMA-NDF, the clad-to-core diameter ratio was set to a value close to 4, imposing either a multimode core or a very small inner cladding. Here, we study a 30/125 μm LMA NDF with clad-to-core ratio of 4.2 and also explore for the first time the possibility of LMA fibers with higher clad/core ratios and very low core NA to maintain nearly diffraction-limited output beam in a fully fiberized MOPA

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Raphaël Florentin, Hervé Gilles, Sylvain Girard, and Mathieu Laroche are with the Centre de recherche sur les ions, les matériaux et la photonique, ENSICAEN-CNRS-CEA, Normandie Université, 14032 Caen, France (e-mail: raphael.florentin@ensicaen.fr; herve.gilles@ensicaen.fr; sylvain.girard@ensicaen.fr; mathieu.laroche@ensicaen.fr).

Kilian Le Corre, Thierry Robin, and Alexandre Barnini are with Exail (formerly iXblue), 22300 Lannion, France (e-mail: kilian.le-corre@exail.com; thierry.robin@exail.com; alexandre.barnini@exail.com).

Roopa Prakash and Giorgio Santarelli are with LP2N, 33400 Talence, France (e-mail: roopa.prakash1@institutoptique.fr; giorgio.santarelli@institutoptique.fr).

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TABLE I
RELEVANT CROSS-SECTION IN A ND-DOPED SILICA FIBER [20]

	σ_{abs}^{808}	σ_{abs}^{915}	σ_{em}^{915}	σ_{em}^{1050}
Cross-section (cm^2)	1.2×10^{-20}	8×10^{-22}	6×10^{-21}	1×10^{-20}

system. The impact of this ratio on laser performances was experimentally investigated. In addition, we demonstrate numerically and experimentally that precise bending of the low-NA LMA-NDF could play an important role in both high-order mode filtering and spectral filtering to limit the onset of ASE around 1050 nm.

II. Simplified Analytical Model to Estimate the Influence of the Clad-to-Core Diameter Ratio on the Unsaturated Gains at 915 nm and 1050 nm

First, it is important to understand how the clad-to-core diameter ratio R affects the gains at 915 nm and 1050 nm in a cladding-pumped NDF. Basically, the idea is to lower the gain of the four-level transition in order to avoid strong ASE at 1050 nm while maintaining the gain of the three-level transition near 915 nm at a value between at least 10 to 20 dB. For this purpose, the energy level diagram of Nd ion can be simplified by considering only the two main energy levels involved in the laser transition around 915 nm. Here, N_1 is the population density of the fundamental level E_1 ($^4I_{9/2}$) and N_2 is the population density of the emitting level E_2 ($^4F_{3/2}$). Considering a homogeneous population inversion along the fiber and a perfect overlap between lasing modes and the doped core area, the unsaturated single-pass gains respectively at 915 nm (1) and 1050 nm (2) are defined as:

$$G^{915} = e^{\left(\sigma_{em}^{915}.N_2 - \sigma_{abs}^{915}.N_1\right).L} \quad (1)$$

$$G^{1050} = e^{\left(\sigma_{em}^{1050}.N_2\right).L} \quad (2)$$

with L the length of the NDF, σ_{em}^{λ} and σ_{abs}^{λ} respectively the stimulated emission and absorption cross-sections at the wavelength λ.

By defining the merit factor as $\mathrm{MF} = \frac{G^{915}}{G^{1050}}$, the population fraction in the emitting level as $\eta = \frac{N_2}{N_t}$ where $N_t = N_1 + N_2$ and combining (1) and (2), MF can be expressed as:

$$MF = e^{\left(\sigma_{em}^{915}+\sigma_{abs}^{915}-\sigma_{em}^{1050}\right)\eta - \sigma_{abs}^{915})N_t.L} \quad (3)$$

According to the effective cross-section values reported in Table I, MF is inherently lower than 1, which means that the gain at 1050 nm will always be higher than the gain at 915 nm. Hence, the only way to increase MF is to reduce the fiber length L and/or the Nd^{3+} ions concentration N_t. However, it will reduce the pump absorption. The unsaturated transmission of a double-clad fiber at the pump wavelength can be approximated by the modified Beer-Lambert's equation:

$$T_{808} = e^{-\frac{\sigma_{abs}^{808}}{R^2}N_t.L} \quad (4)$$

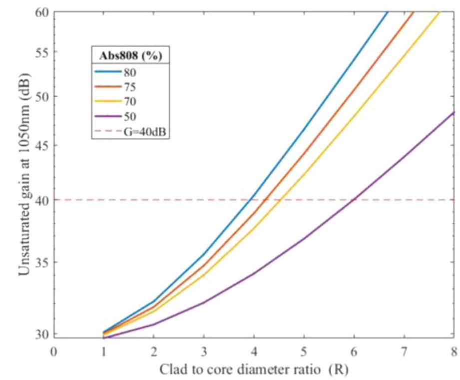

Fig. 1. Unsaturated gain at 1050 nm calculated from (1) and (3) as a function of clad-to-core diameter ratio R for a fixed gain at 915 nm of 20dB and for an unsaturated pump absorption varying between 50% and 80%.

TABLE II
PARAMETERS OF THE ND-DOPED LMA FIBERS WITH A HIGHER CLAD-TO-CORE RATIO

Core diameter (µm)	Clad diameter (µm)	Clad-to-core ratio	Core NA	Normalized Frequency V (@915nm)	Absorption @808 nm (dB/m)
15	100	6.7	0.06	3.09	1.7
20	100	5	0.06	4.20	1.7
30	125	4.2	0.045	4.63	0.96

To compensate for the resulting decrease in pump absorption, it becomes therefore necessary to reduce R. By setting the values of the ratio R and the unsaturated pump absorption, the product Nt×L is also known, so that the gains at both wavelengths now only depend on the population inversion η. In the following, we arbitrarily choose an unsaturated gain at 915 nm of 20 dB, which is a realistic value for both amplifier and laser configurations. The evolutions of the unsaturated gain at 1050 nm versus the ratio R for different pump absorption values varying between 50% and 80% are shown in Fig. 1. Note that the pump absorption values are estimated here in unsaturated regime, hence using the absorption coefficients specified by the manufacturer (see Table II). Assuming that the gain at 1050 nm must remain lower than 40 dB to avoid a strong ASE on this transition, we can then estimate that the R ratio must be less than or equal to 4 for a fiber with a usual pump absorption of ~80%. Hence, this simple calculation confirms the previous experimental observations. However, it is interesting to note that reducing the absorption to 50% would allow for R to increase to 6, but at the expense of the laser efficiency with respect to the injected pump power.

It is also important to notice that reducing the Nd^{3+} ions concentration, in addition to promoting the gain at 915 nm compared to the gain at 1050 nm, would also limit the clustering effect of Nd^{3+} ions. Indeed, it has been shown that the clustering of Nd ions in silica fiber has an extremely detrimental effect on the laser efficiency near 900 nm [21]. However, using a ratio of 4, maximum laser slope efficiencies as high as 52% at 910 nm (with respect to the injected pump power) have already been reported

[15], which suggests that this R value is generally sufficient to limit the cluster formation.

Considering that a NA of 0.045 is the minimum value to ensure sufficient modal stability in a flexible step-index fiber, a true single-mode propagation at 915 nm would require a maximum core diameter of 14 μm and therefore a clad diameter of 60 μm using a ratio R = 4. Meanwhile, this geometry is not suitable for high-power pumping (>100 W) and easy integration into all-fiber MOPA systems. Hence, the specific case of the LMA NDF design is a multi-parameters problem and finally corresponds to a compromise between laser efficiency, beam quality and ease of integration into a fully-fiberized high-power MOPA system. Using a step-by-step approach, a 30/125 fiber geometry was first developed to keep a ratio R $\sim$ 4 while having a clad diameter adapted for high power pumping and standard pump signal combiners.

III. Characterization of a Low-NA 30/125 NDF

A. Fiber Core Composition

Glass composition of a low-NA NDF is subject to two constraints: the limitation of Nd^{3+} clustering and a very low step index between the core and the clad. Phospho-alumino-silicate (SiO_2-Al_2O_3-P_2O_5-Nd_2O_3) can partially fulfill these two requirements. Whereas neodymium or aluminum alone tends to increase the refractive index compared to pure silica glass, the two co-dopants - Aluminum + Phosphorus - simultaneously added into silica glass may decrease the refractive index [22]. The minimum refractive index is obtained for a ratio Al/P = 1. Bubnov et al. [23] also demonstrated that the refractive index of the glass decreases when the amount of equimolar Al/P increases. In addition, the phospho-alumino-silicate composition also promotes the solubilization of neodymium ions, thus effectively reducing cluster formation. The fabricated LMA NDF with 30/125μm core/clad geometry (ratio R = 4.2) has a core NA of 0.045. Consequently, three higher-order modes (HOM) can theoretically be guided, which may strongly deteriorate the output beam quality without any other mode selection.

B. Amplification Using Free-Space Signal Injection

It is well known that selective propagation losses can apply to HOMs in a bent LMA fiber having a low NA. In addition, bending losses also increase at longer wavelengths, which can be advantageously used to reduce the effective fiber gain near 1050 nm without affecting the gain near 915 nm [24], [25]. Experimental and numerical studies of the effect of bending losses on the fiber performances have been carried out, in particular to determine whether modal and spectral filtering could be effective simultaneously. A homemade MOPA laser source based on single-mode Nd doped fibers, capable of delivering up to 1.4 W output power at 915 nm in a diffraction-limited beam, is free-space injected into the 30/125 LMA NDF using a pair of lenses to ensure mode matching. In the following, the fiber amplifiers are also systematically backward pumped in free-space by a multimode laser diode at 808 nm. A pump power up to 23 W is injected into the fiber clad. The fiber length is adjusted to 7 m in order to absorb 80% of the injected pump. The fiber can be coiled around cylinders of various diameters to change the radius of curvature (RoC) applied to the fiber. The output power of the amplified signal at 915 nm and the ASE power near 1050 nm are measured simultaneously after a dichroic mirror. An iris diaphragm was also systematically used to eliminate power that could be guided into the fiber clad in the event of tight fiber bending. For each RoC, the M^2 factor of the output beam at 915 nm was measured using standard scanning technique based on a beam profiler (WinCamD-LCM).

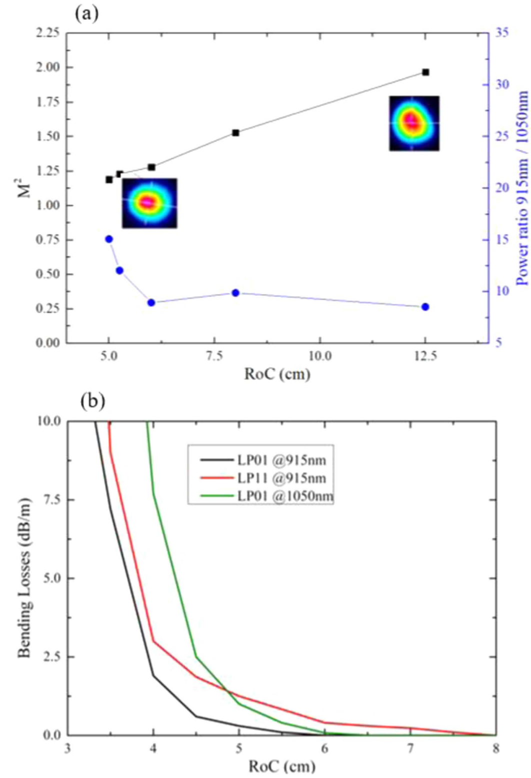

Fig. 2. (a) Evolution of M^2 and power ratio 915 nm/1050 nm as a function of radius of curvature applied on the 30/125 LMA fiber in amplifier configuration; (b) Calculated bending losses for LP_{01} and LP_{11} modes at 915 nm and for LP_{01} mode at 1050 nm as a function of the radius of curvature of the LMA fiber.

Fig. 2(a) (black curve) shows the evolution of the M^2 factor measured at the output of the amplifier as a function of the RoC applied to the fiber. M^2 value decreases almost linearly from 2 to 1.2 when the bending radius applied to the fiber is reduced from 12.5 to 5 cm. For bending radius smaller than 5 cm, we observed a decrease in the output power at 915 nm without any improvement of the M^2 value. The Fig. 2(a) (blue curve) also gives the ratio between the amplified signal power at 915 nm and the ASE power near 1050 nm at the output of the amplifier. This ratio rapidly increases for a RoC below 6 cm and is multiplied by a factor of 3 for a RoC equal to 5 cm. This result confirms that the bending of the NDF can also induce a selective spectral filtering which is sufficient to effectively reduce the ASE power at 1050 nm. With a bending radius near 5 cm, for 1 W of signal power coupled in the fiber core and 23 W of injected pump power, the amplified output power at 915 nm is 8.4 W whereas the ASE output power at 1050 nm is limited to about 500 mW. This value of RoC that maximizes the output power at 915 nm while improving the beam quality will be referred as the optimal bending radius in the following.

Propagation losses of LP01 mode at 915 nm and 1050 nm and of the first HOM LP11 at 915 nm were calculated as a function of RoC using the BPM-Matlab simulation tool [26]. For that purpose, a 30 μm core diameter fiber with a step-index profile (NA = 0.045) was considered. Results are given in Fig. 2(b). By comparing the calculated losses at 915 nm relative to LP01 and LP11 modes, one can notice that for a RoC between 5 cm and 8 cm, only the LP11 mode undergoes significant losses. The maximum differential propagation loss is about 1.2 dB/m, which may not be sufficient to completely suppress a HOM injected at the fiber input but would greatly reduce its amplification in a saturated amplifier of a few meter long. In addition, it may help to counteract intermodal coupling from the fundamental LP01 mode to HOMs. One can also deduce from Fig. 2(b) that there is a small RoC range between 5 cm and 6 cm for which the LP01 mode at 1050 nm suffers from significant propagation losses compared to the same mode at 915 nm, as already observed experimentally. The loss coefficient is limited to 1 dB/m for a RoC of 5 cm but rapidly increases to 2.5 dB/m for a slightly smaller bending radius of 4.5 cm. Hence, this numerical simulation tends to confirm, for this specific 30/125 NDF, the possibility of simultaneous efficient spectral and modal filtering.

C. Amplification Using Fiberized Signal Injection

All-fiberized amplifiers without any free-space propagation part are essential to build a robust and reliable MOPA laser system. For that purpose, a mode field adapter (MFA) is usually used to reduce the coupling losses between two fibers with different core diameters. However, these components are difficult to manufacture and generally do not guarantee perfect mode matching. Here, the output fiber of the homemade laser source at 915 nm is a single-mode fiber (PM850). A custom commercial MFA (Haphit) was designed to ensure mode matching between this single-mode fiber (input) and a passive version of the double-clad 30/125 NDF (output), which is spliced to the 30/125 NDF coiled at its optimal bending radius. The LMA fiber length is the same as the one used in the previous experiment (L = 7 m). The M^2 at the MFA output was measured equal to 1.45 which shows slightly multimode propagation in the passive 30/125 fiber. To measure the conversion efficiency of the amplifier at 915 nm, the injected signal power is set at 450 mW. The saturation of the amplifier at 915 nm was also evaluated for a pump power of 23 W and an injected signal power from 0 to nearly 500 mW. The output powers at 915 nm and 1050 nm for these two experiments are shown in Fig. 3(a) and (b), respectively.

At the maximum output power of 7.1 W at 915 nm, the amplifier efficiency is about 31% while the ASE power at 1050 nm is limited to 700 mW, which corresponds to a similar efficiency compared to the free-space signal injection, given a lower injected signal power. The gain at 915 nm is equal to 17 dB when the amplifier is injected with a small input signal of 40 mW and decreases to 12 dB when the input signal reaches 488 mW. The initial gain and the saturation power of the amplifier are estimated to about 19 dB and 60 mW, respectively. This gain value is much lower than for other common rare-earth doped fiber amplifiers, which can be explained by the ASE at 1050 nm limiting the population inversion. Furthermore, ASE power at 1050 nm and then initial gain and saturation power all depend on the bending radius of the fiber.

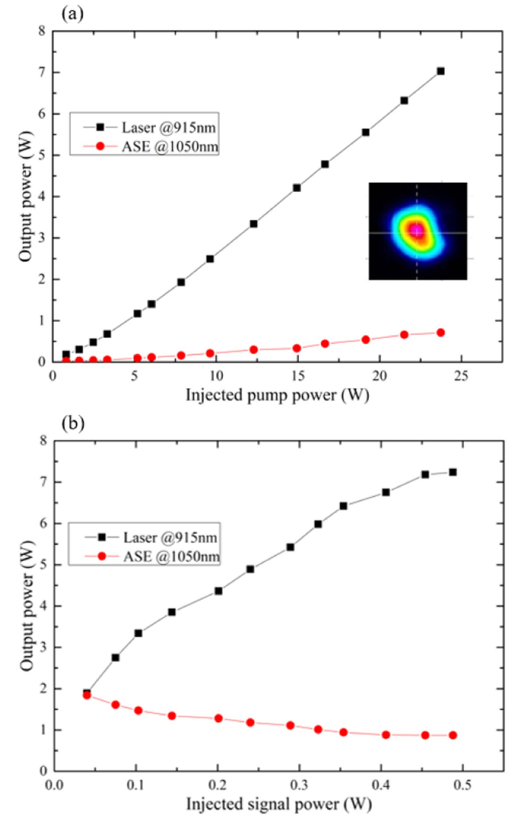

Fig. 3. Output powers at 915 nm and 1050 nm of the 30/125 LMA fiber amplifier injected through a MFA, (a) versus pump power for an injected signal power of 450 mW and (b) versus injected signal power for an injected pump power of 23 W. In black: Laser power at 915 nm; in red: Forward ASE power at 1050 nm; Insert: Signal beam profile at the maximum output power.

The 2D intensity profile of the output beam (see insert in Fig. 3(a)) clearly shows a multimode behavior, which is confirmed by the measured beam quality factor $M^2 = 1.8$. This poor value of the beam quality factor can be explained by the degraded beam at the MFA output. In this case, the losses induced by the fiber bending are not sufficient to completely avoid the amplification of HOMs. These observations confirm the need to develop new LMA NDFs for intermediate amplifiers before the final power amplifier in a high power MOPA laser system. In order to reduce the saturation power and improve the output beam quality, it appears necessary to decrease the core diameter for such intermediate amplifiers. Therefore, since a large clad diameter (>100 μm) is required for high power pumping and to facilitate splicing with other standard fiber components, the ratio R must inevitably be increased.

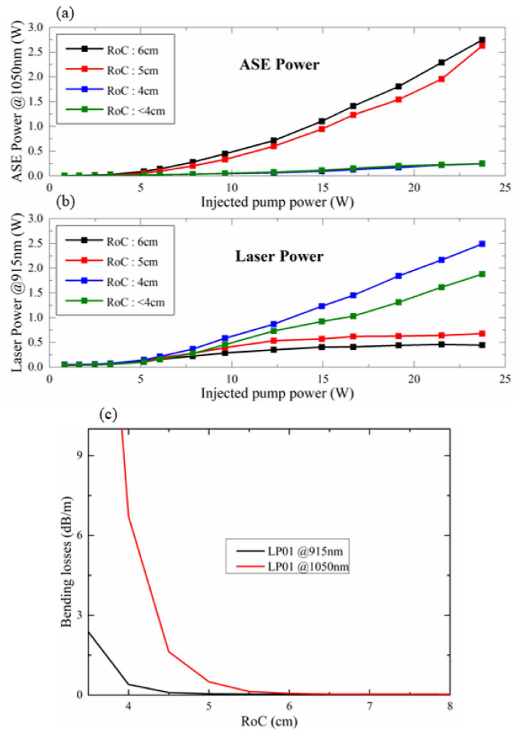

Fig. 4. Output powers from the 15/100 LMA fiber amplifier for different radius of curvature (a) 1050 nm ASE power (b) amplified laser signal at 915 nm (c) calculated bending losses for the LP01 mode at 915 nm and at 1050 nm as a function of the radius of curvature of the LMA fiber.

IV. LMA NDF With Clad to Core Ratio of 5 and 6.7

Using similar phospho-alumino-silicate core compositions as for the previous 30/125 LMA fiber, two new Nd-doped LMA fibers have been developed, whose parameters are summarized in Table II. It should be noted that these new fibers have a NA of 0.06, which facilitates the manufacture of the fibers and also makes them less sensitive to macro-bending.

According to the results from the analytical study presented in Fig. 1, these two fibers should present a higher gain at 1050 nm, so that the growth of ASE at 1050 nm needs to be counteracted by bending the fiber to a tighter radius, taking into account that modal and spectral filtering should be more effective on these fibers due to their smaller core diameters. To test this hypothesis, the single-mode laser source at 915 nm is now spliced to a passive single-mode PM fiber with a larger core diameter of 10 μm (LIEKKI Passive-10/125-PM). The 15/100 Nd-doped LMA fiber under test has a Nd concentration increased by a factor ~2 (L = 4.1 m for a pump absorption of 80%) and is spliced directly to this passive fiber. In this experiment, we chose to limit the injected signal power at 915 nm to 100 mW, so as to be in the case of a medium power amplifier. The output powers at 1050 nm and 915 nm were measured as a function of the pump power for different RoC, as represented in Fig. 4(a) and (b).

As expected for this clad-to-core ratio, when the fiber is not tightly bent (RoC > 5 cm), ASE power at 1050 nm is much higher than the signal power at 915 nm. As for example, for a RoC of 6 cm, measured power ratio between 915 nm and 1050 nm is only 0.16. However, for a RoC equal or below 4 cm, the 1050 nm ASE power is rapidly reduced to only 250 mW. At the same time, the amplified power at 915 nm is increasing from 0.5 W up to 2.5 W for an optimized bending radius of 4 cm, corresponding to a power ratio of 10.2. The pump-to-signal conversion efficiency at 915 nm is only 11%, which can be explained by the tight bending inducing losses at 915 nm and probably a higher level of Nd ions clustering. For a RoC smaller than 4 cm, the output power at 915 nm starts to decrease due to excessive bending losses.

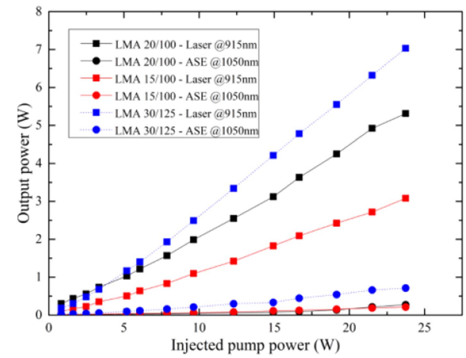

Fig. 5. Amplified output powers at 915 nm and ASE power at 1050 nm versus pump power for an injected signal power of 450 mW. All the three LMA-NDF were coiled at their optimal bending radius.

In order to confirm these experimental observations, we calculated the losses induced by the bending for a LP01 mode, respectively at 915 nm and 1050 nm using BPM-Matlab simulation code (Fig. 4(c)). These results confirm that a radius of curvature < 5 cm is necessary to induce high propagation losses (> 1dB/m) at 1050 nm. Once again, the optimal range for the RoC is very narrow and still in very good agreement with the experimental observations. As already mentioned, this fiber with a smaller core diameter allows higher bending losses at 1050 nm compared to the 30/125 LMA fiber. As for example, more than 6 dB/m losses can be achieved at 1050 nm with limited losses of 0.5 dB/m at 915 nm. The same experimental and numerical studies were done with 20/100 LMA NDF and, in this case, the optimal bending radius was found equal to 5 cm.

For these two fibers, the M^2 beam quality factor is close to 1 when the fiber is properly coiled: 1.06 for the 15/100 LMA fiber and 1.09 for the 20/100 LMA fiber. These results confirm that the combination of a reduced core diameter and a well-optimized fiber bending radius lead to a significant improvement in beam quality compared to 30/125 fiber.

In order to compare the laser performances of the three LMA fibers, their conversion efficiencies were estimated in all-fiber amplifier configuration and under similar experimental conditions. The injected signal power at 915 nm is fixed to 450 mW, the fiber length is adjusted to achieve a pump absorption of 80% and each fiber was bent at its optimal bending radius. The comparative results are presented in Fig. 5.

Maximum conversion efficiencies of 23% and 13% were respectively measured for 20 μm core diameter and 15 μm core diameter LMA fibers, which is still lower than the efficiency of 31% measured for the 30/125 fiber. This can be explained by the presence of clusters due to much higher Nd doping levels, and the fact that high clad-to-core ratio fibers must be more strongly bended to counteract a very high gain at 1050 nm. This is particularly the case with 15/125 LMA fiber for which the optimal bending radius is about 4 cm, which represents a propagation loss of 0.5 dB/m at 915 nm according to the calculations presented in Fig. 4(c). As a consequence, this fiber would only be adapted to a low gain / high beam quality amplifier. The 20/100 NDF represents a better compromise in terms of conversion efficiency and beam quality for an intermediate power amplifier. These intermediate diameter fibers developed in this work are therefore complementary to the 30/125 LMA fiber and thus allow to build all-fiber amplifiers with multi-watts output power, nearly single-mode output beam and low spurious ASE power at 1050 nm.

V. Conclusion

In this article, we report a comprehensive study of the relationship between the clad-to-core diameter ratio in Nd-doped LMA fibers and their amplifying properties near 915 nm using $^4F_{3/2} \rightarrow {}^4I_{9/2}$ laser transition. Based on an analytical study and numerical BPM simulations, three different Nd-doped LMA fibers have been designed to study experimentally the impact of the clad-to-core ratio on both amplifying efficiency and beam quality factor. The 30/125 LMA fiber amplifier with a clad-to-core ratio of 4 allows an optimal power extraction (efficiency $> 31\%$) at 915 nm, at the expense of beam quality. Intermediate clad-to-core ratio fibers ($R = 5$-7) allow to target applications for which beam quality is essential. The production of PM versions of these fibers should allow achieving several watts of linearly polarized output power in a nearly single-mode beam. These Nd-doped LMA fibers may therefore pave the way for the realization of an all-fiber MOPA emitting tens of watts at 915 nm, which would be particularly suitable for CW single-frequency or short pulse amplification.

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