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ABSTRACT

A polarization-maintaining Yb-doped large mode area fiber with depressed-index inner cladding layer and confinement of rare-earth dopants has been drawn as a long tapered fiber. The larger end features a core/clad diameter of 56/400 µm and core NA ~ 0.07, thus leading to an effective mode area over 1000 µm^2. The fiber was tested up to 100 W average power, with near diffraction-limited output as the beam quality M^2 was measured < 1.2. As effective single-mode guidance is enforced in the first section due to enhanced bending loss, subsequent adiabatic transition of the mode field in the taper section preserves single-mode amplification towards the larger end of the fiber.

Keywords: Fiber amplifier, Large mode area, Ytterbium, Taper, Depressed cladding, Dopant confinement, Beam quality

1. INTRODUCTION

Large mode area (LMA) fibers have been instrumental to the tremendous progress seen by high power fiber lasers in the past fifteen years[1-2]. Mitigation of nonlinear effects has pushed forward the development of active fibers with larger core diameter and lower NA following various innovative designs[3-4]. As most LMA fibers are not intrinsically single-mode, waveguide designs have to rely upon a distinctive mechanism to suppress higher-order modes (HOMs) and thus effectively enforce single-mode guidance. Modal discrimination may be achieved either through preferential amplification of the fundamental mode or by imparting higher losses to HOMs. The former may rely either on confinement of rare-earth dopants to the core center, where overlap with fundamental mode is greatest, or otherwise on delocalization of HOMs outside the core region, such as to make excitation and amplification of these modes less likely. On the reverse, designs that depend on propagation losses often require the fiber to be coiled for the HOMs to escape from the core. As the core diameter gets larger (> 50µm), achieving effective single-mode operation from few-mode fibers becomes increasingly difficult given the collapse of the effective index space and subsequent vanishing mode discrimination.

Tapered fibers have emerged as a distinctive approach where scaling to large mode areas naturally occurs along the length of the fiber, often starting as single-mode at launching end[5-6]. Adiabatic transition of the fundamental mode between the smaller and larger ends of the tapered fiber is expected to yield near diffraction-limited beam profiles at the larger end. The tapering process is usually performed during fiber drawing and so great accuracy may be achieved on core/clad diameters along the transition between both ends. Large taper ratios (> 10) were shown recently to yield unprecedented mode areas, but most often at the expense of small core/clad ratio and long amplifier fiber length. The latter in turn raises the question of power scalability because of weak pump absorption as well as early onset of nonlinear effects. Besides, irregular index profiles is likely to yield increasingly distorted beam profiles for larger core diameters, sometimes far from being diffraction-limited[7].

Here we report on a very large mode area Yb-doped tapered fiber featuring confined doping and depressed-index inner cladding for enhanced modal discrimination[8-9]. The larger end features core/clad diameter of 56/400 µm and core NA ~ 0.07, thus leading to effective mode area over 1000 µm^2. As effective single-mode guidance is enforced in the first section due to enhanced bending loss, subsequent adiabatic transition of the mode field in the taper section is shown to preserve single-mode amplification towards the larger end of the fiber. Besides, the comparatively high pump absorption and short taper length are shown to be strong arguments for this fiber to be considered as a solution to the scalability problem. In the following we first provide details about the fiber design as well as the waveguiding properties inferred from refracted near-field index measurement. Performances as a power amplifier in various conditions are discussed thereafter in the light of the above comments and finally an outlook is given to conclude.

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2. LMA TAPERED FIBER

A polarization-maintaining LMA tapered fiber doped with ytterbium has been drawn using precision variable feedback controls during fibre-draw process, starting from a fiber preform fabricated through conventional MCVD and solution doping process (see Fig. 1(a)). The fiber core/cladding has a diameter of 35/250 µm in the smaller end and 56/400 µm in the larger end, thus resulting in a taper ratio of 1.6 (see Fig. 1(b)). The refractive index profile features a small depression at the inner portion of the 1st cladding layer such as to enhance HOMs bending loss. The core NA was determined to be ~ 0.07 from refracted near-field measurement. Using a finite-difference mode solver, the effective mode area is predicted to scale from approximately 500 µm^2 in the smaller end to over 1000 µm^2 in the larger end (see Fig. 1(b)). The taper section providing for adiabatic transition of the mode field between both plateaus is approximately 0.8 m long. The applied low-index polymer coating gives a pump guide NA of 0.50. The fiber birefringence was measured to be as high as $1.7 \cdot 10^{-4}$.

The refractive index depression of the inner cladding layer has been engineered such as to enhance the differential bending loss between LP_{01} and LP_{11} modes in the 35/250 end of the tapered amplifier fiber (see Fig. 2(a)). If not careful

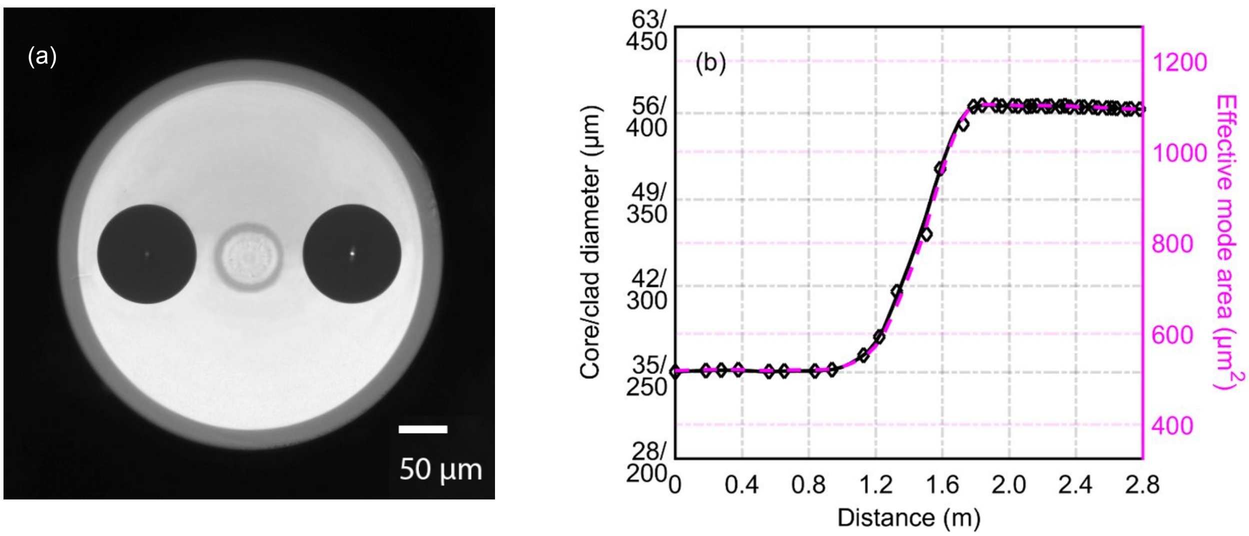


Figure 1 – (a) Optical micrograph of a 56/400 µm section of the LMA tapered fiber and (b) measured core/cladding diameters (straight line) and calculated effective mode area (dashed line) along the tapered fiber.

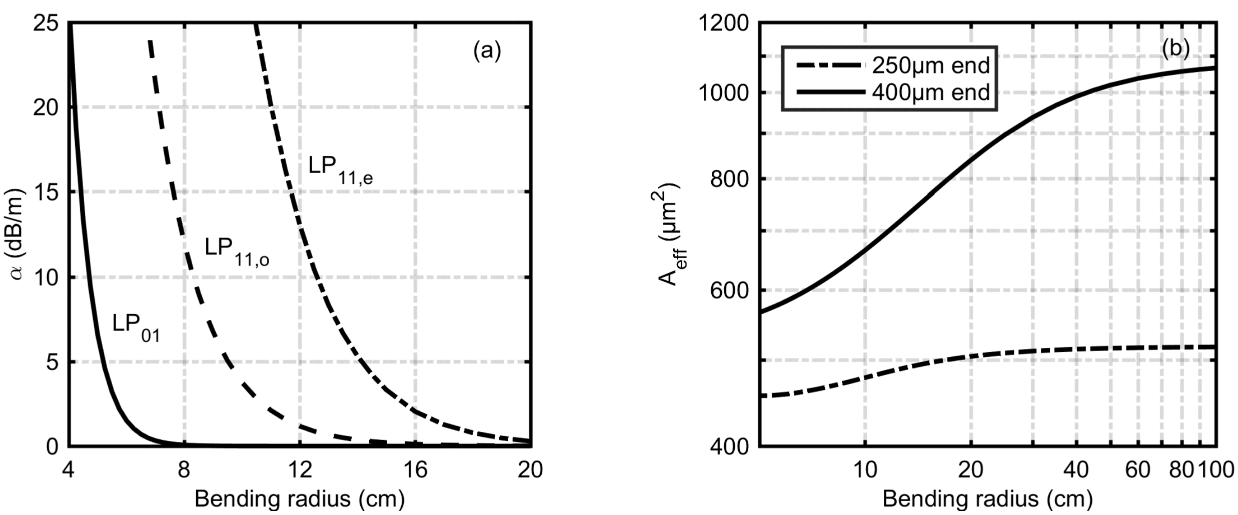


Figure 2 – (a) Bend-induced propagation losses for 35/250 µm section and (b) effective mode area of LP_{01} mode for both 35/250 and 56/400 µm sections of the LMA tapered fiber as a function of the bending radius.

with the launching conditions, then one may decide to coil the fiber in order to selectively excite the fundamental mode before the signal propagates through the taper transition towards the larger end. For instance, differential bending loss between LP_{01} and LP_{11} modes > 10 dB/m are readily achieved with reasonable coiling diameters (< 16 cm). The enhanced bend-induced loss attributed to the depressed-index cladding layer is not based on a resonant coupling of HOMs to the cladding structure. Instead, suppression of HOMs becomes simply more efficient once the fiber is coiled, as the evanescent field of HOMs extends further beyond the depressed-index cladding layer, thus lowering the effective numerical aperture of HOMs because of the greater overlap with outer cladding region.

As the fiber is coiled though, one has to be mindful about the effective mode area shrinking due to bend-induced mode distortions. The latter is especially true for fibers with very large mode area, where reduction of the effective mode area will severely impair the mitigation of nonlinear effects[10]. This is better illustrated in Fig. 2(b) where the effective mode area for LP_{01} mode is shown for both ends of the tapered fiber as a function of the bending radius. While reduction of the mode area due to bend-induced distortion is lower than 10% for the smaller end, the same cannot be said for the larger end as the reduction almost reaches 50% for small coiling radii. In other words, even though it is perfectly acceptable to coil the smaller end in order to facilitate the suppression of HOMs, a looser coiling is required for the larger end in order to benefit from the full potential of this fiber.

The core chemical composition of the fiber is based on phosphorus/aluminum co-doped silica glass. Co-dopants concentration ratio (P_2O_5/Al_2O_3) was adjusted such as to minimize photodarkening losses[11]. Besides, the formation of $AlPO_4$ compounds allows for higher ytterbium doping levels and yet keeps to a minimum the core-cladding refractive index difference. The confinement factor of ytterbium dopants in the core (about 2/3) is near optimal. Pump absorption was measured as 2.7 dB/m and 10.8 dB/m at wavelengths of 915 nm and 976 nm, respectively. The preferential amplification of LP_{01} mode is strongest in the smaller end of the tapered fiber as the overlap difference between LP_{01} and LP_{11} modes with the ytterbium dopants is predicted to decrease as the mode area is scaled along the taper transition. Photodarkening losses have been measured to be very low through a lifetest running for over 500 hours uninterrupted.

3. EXPERIMENTS

The active tapered fiber has been tested as a power amplifier using a coherent 1064 nm seed laser with 0.5 W CW average power. Signal light was launched at the smaller end while 976 nm pump light from wavelength-stabilized laser diodes (200µm – 0.22NA) was launched at the opposite end (see Fig. 3). Both fiber ends were cut approximately 1.0 m away from proper taper transition, so total amplifier fiber length was 2.8 m (see Fig. 1(b)). The smaller end was coiled on a spool according to various diameters to test for HOMs suppression while the remainder was loosely coiled (so as to avoid mode area shrinking). Average output power close to 100 W has been obtained, with a slope efficiency of 84% as defined with respect to incident pump power (see Fig. 4(a)). Besides, the loss of pump light due to vignetting is not expected as the pump brightness is sufficiently high for the fill factor to sit well below the effective NA (= 0.31) above which the light propagating from the larger end through the taper transition to the smaller end is not confined anymore. The polarization extinction ratio was superior to 18 dB over the complete interval with the seed polarization aligned along the slow axis of the tapered fiber.

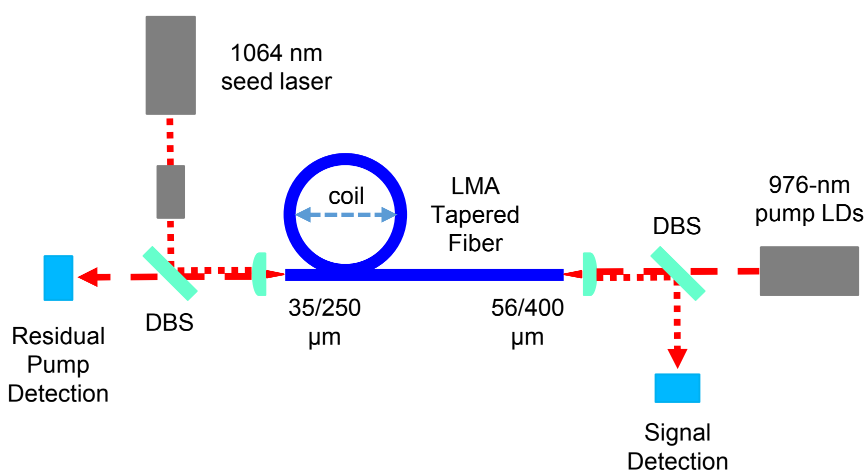


Figure 3 – Schematic representation of the experimental setup used to test Yb DCOF 35/250-56/400-PM LMA tapered fiber

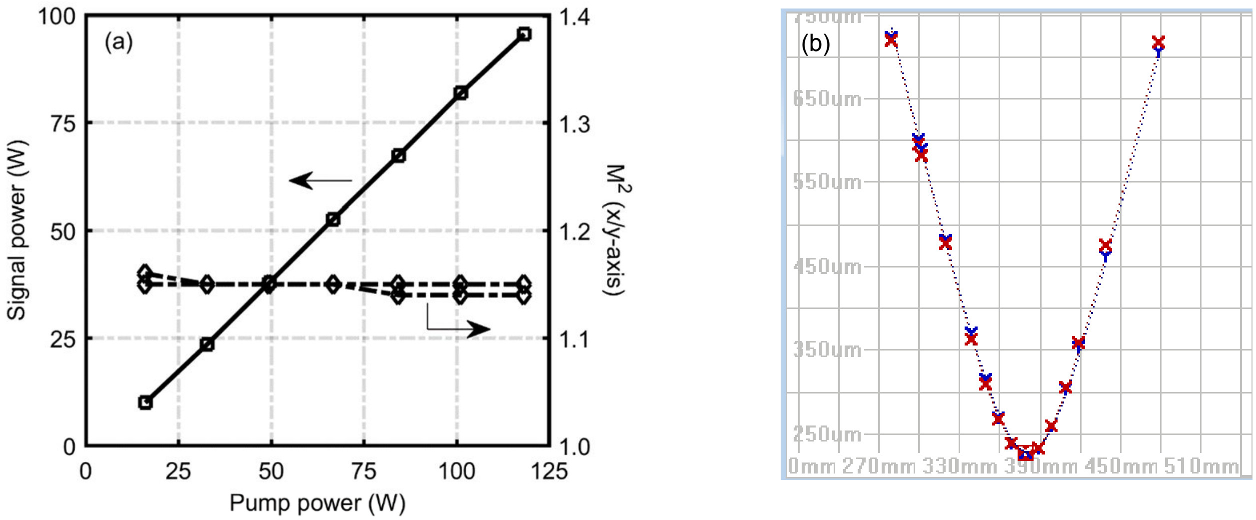
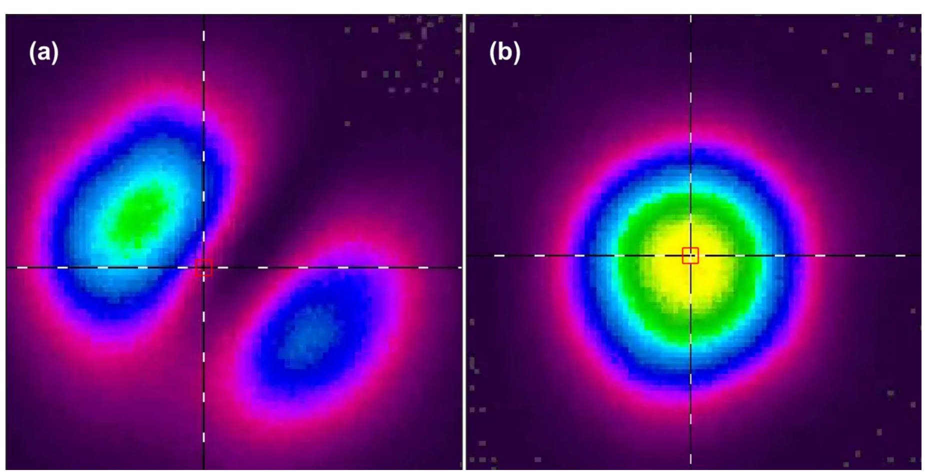


Figure 4 – (a) Amplifier slope efficiency (left axis) and beam quality factor M^2 (right axis) along with (b) one of the M^2 datasets as performed with M2-200s beam propagation analyzer from Ophir-Spiricon ($M^2_{x,y} = 1.15$).

Near diffraction-limited output was obtained as the beam quality factor M^2 was measured < 1.2 for both x/y-axis (see Fig. 4(b)). Interestingly, our finite-difference mode solver yields an M^2 factor of 1.1 for LP_{01} mode upon propagation along the larger end of the tapered fiber. This is to be expected as deviations from a perfect step-index profile will cause more noticeable distortions to mode intensity profiles for larger core diameters. The fiber was never coiled so tightly so as to cause excessive loss for the fundamental mode and consequently impair the amplifier efficiency. In addition, the M^2 factor did not change significantly with looser coiling diameters at the smaller end, which is an indication of appropriate launching conditions.

Suppression of HOMs is further evidenced by the beam profiles shown on the CCD video captures in Video 1. There, the incident mode-matched Gaussian beam launched on the signal end was steered off the fiber input end by as much as 10 μm from optimal launching conditions to deliberately excite HOMs (with coupling to LP_{11} estimated > 30 %) for both loosely and tightly coiled small end section. The difference is striking: while the beam profile on Video 1(a) gets more and more distorted as LP_{11} mode shows up, the near single-mode beam of Video 1(b) stays fairly circular with no obvious sign of HOMs. As effective single-mode guidance is enforced in the first section through enhanced HOMs bending loss, subsequent adiabatic transition of the mode field in the taper section preserves single-mode amplification towards the larger end of the fiber. Also shown is the excursion of the beam centroid normalized to the beam waist size.



Video 1 – Beam profile for (a) loosely coiled (40 cm dia.) and (b) tightly coiled (14 cm dia.) smaller fiber taper end while launching of incident mode-matched beam is offset from 0-10 μm. http://dx.doi.org/10.1117/12.2250864.1

Interestingly, the beam centroid is seen to move very little, with root-mean-square excursion < 2%. Besides, the latter is assumed to be largely due to mechanical constraints introduced by fiber packaging as similar random fluctuations are seen to occur under ideal launching conditions.

Perhaps the most interesting observation lies in the beam quality measurements for high gain levels (30-40 dB), i.e. as ASE grows up to be a sizeable fraction of the total output power (10-30%). At first glance, the M^2 factor seems to get worse but looking more closely does reveal some very interesting facts. Using a high rejection filter to split the ASE background from the amplified pulse train allows to measure separately the characteristics of each. In doing so it was seen that the M^2 factor of the amplified signal does not actually increase much while the M^2 factor of the ASE background evidently does (see Fig. 5(a)). The ASE beam profile was resolutely LP_{11} (as seen from the inset), only here the x/y measurement axes were not aligned with the two-lobe intensity profile, hence the $M^2 < 3$. So while the signal is confined in the fundamental mode with the gain depleted at the core center, ASE mostly builds up from the gain left for HOMs in the periphery. The latter is believed to be an additional proof of the superior capability of our fiber to carry the signal light in the fundamental mode. Although this could not be checked experimentally, here we theorize that the slight degradation observed with respect to the amplified signal is due to the in-band ASE that could not get blocked by the rejection filter. A stronger confinement of ytterbium ions would likely decrease the ASE, but at the expense of lower gain and longer effective fiber lengths.

The same Yb-doped LMA tapered fiber has been seeded with ps pulses to explore the nonlinear amplification regime. The energy per pulse was scaled up to 50 μJ in the amplifier without ever reaching the Raman scattering threshold, for an impressive peak power close to 1.5 MW. SPM-induced spectral broadening occurred along with the strong oscillatory modulations characteristic of this phenomenon[12] (see Fig. 5(b)). From the latter we could infer a peak nonlinear phase shift (or B-integral) of 15π rad, which is also consistent with the broadening factor retrieved from the RMS width of the optical spectra. The small distortion in the SPM-broadened spectra results from the superimposed coherent red-shifted CW component (which is estimated to carry less than a few percent of the total power). It is believed that most of the nonlinear phase shift takes place in the 56/400 μm end of the tapered fiber, i.e. where signal power is the greatest given our counter-pump configuration. Understandably, changing the seed wavelength to the peak emission cross-section of ytterbium (1030 nm) would restrain the broadening as a shorter fiber would be needed.

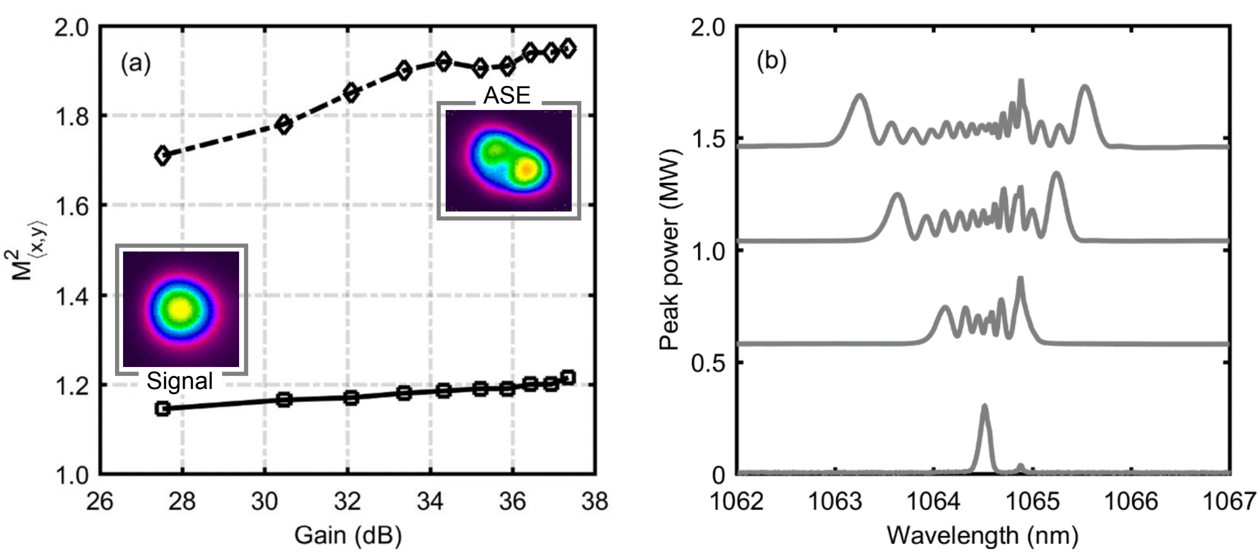


Figure 5 – (a) M^2 factor and beam profiles (inset) as measured for both signal and ASE for high amplifier gain levels (M^2 data here is the average of measurements performed along x/y axes) and (b) SPM-broadened optical spectra through nonlinear amplification of short pulses for different peak powers.

4. CONCLUSION

In summary, a polarization-maintaining Yb-doped LMA fiber featuring depressed-clad and core dopant confinement has been drawn as a long taper with an effective mode area superior to 1000 μm^2 in the larger end. As effective single-mode guidance is enforced in the first section through enhanced HOMs bending loss, subsequent adiabatic transition of the mode field in the taper section preserves single-mode amplification towards the larger end of the fiber. The fiber was tested up to 100 W average power, with near diffraction-limited output as the beam quality M^2 was measured < 1.2. Further evidences of the single-mode behavior have been provided by looking at the beam quality for both signal and ASE separately. Advanced modal characterization techniques such as S^2 imaging[13] are being considered in order to assess with greater sensitivity the mode content of our fiber. The latter requires that the measurement be performed while the gain medium is activated, and not as a passive device as is often the case with this type of test, as preferential amplification owing to dopant confinement is integral part of the design. Investigations are ongoing as whether a larger taper ratio would lead to significant advantages both in terms of mode discrimination and efficiency.

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