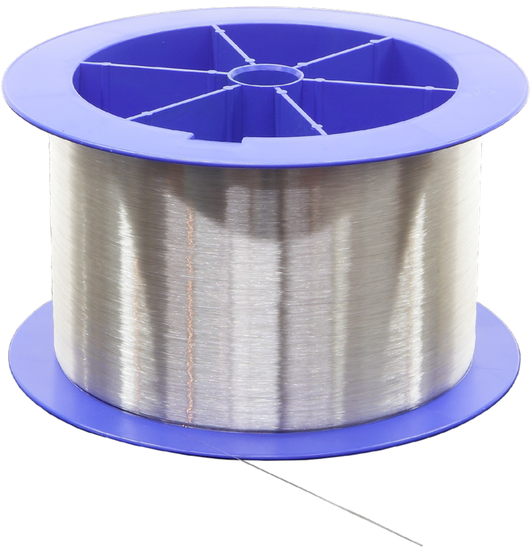

FastFBR Yb-doped PM Optical Fiber Taper

Fundamentals, best practices and performances

White Paper by:

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Introduction

In the field of Large-Mode-Area (LMA) Polarization-Maintaining (PM) optical fiber for high-power pulsed laser amplification, significant efforts are devoted to the constant increase of the effective mode area in order to mitigate nonlinear effects while retaining an optimal beam quality. As the core diameter increases and Numerical Aperture (NA) reduces, various strategies to suppress Higher-Order Modes (HOMs and effectively enforce single-mode guidance must be implemented. The most widely used approach consists of coiling the fiber and relying on differential modal bending losses to filter out the HOMs of slightly multimode fibers and ensure the amplification of the fundamental mode. This strategy is very effective for core diameter up to ~40μm, but become increasingly difficult for larger core due to vanishing mode discrimination.

Tapered optical fibers have recently been proposed as a new approach allowing the scaling to large mode diameter while retaining the convenience and mode-filtering properties of smaller core LMA fibers. In this white paper, we will present the fundamentals of the INO FastFBR[1] Tapered Optical Fiber product , as well as the packaging guidelines and present experimental results of the typical mode quality to be expected with this novel optical fiber.

Tapered optical fiber fundamentals

Tapered optical fiber description and properties

The INO tapered optical fiber (see Fig. 1(a)) is an Yb-doped PM multiclad LMA fiber comprising straight sections of 250 μm and 400 μm linked by a tapered section having a length of ~0.8m. The fiber core/cladding has a diameter of 35/250 μm at the smaller end and 56/400 μm at the larger end, thus resulting in a taper ratio of 1.6 (see Fig. 1(b)). These fiber dimensions yield an effective mode area ranging from 500μm^2 for the 35/250 end up to over 1000μm^2 for the 56/400 end. Since the tapered optical fiber is drawn from a single preform uniform along its length, the core/cladding diameter ratio (CCDR = 0.14), core numerical aperture (NA = 0.07) and absorption (2.5dB/m @ 915nm) remains the same along the length of the taper. The detailed specifications of the FastFBR Yb-MCOF-35/250-56/400-07-2.5-T0.8-PM tapered optical fiber product are presented in Table 1.

[1] See our website at https://www.ino.ca/en/solutions/tapered-fiber/

The mother preform for this tapered optical fiber has been fabricated using the conventional MCVD and solution doping process and is based on an active core composed of Yb-doped phospho-alumino-silicate (Yb:P-Al-Si) glass. Co-dopants concentration ratio (P_2O_5/Al_2O_3) was adjusted such as to minimize photodarkening losses. Another advantage of the P-Al-Si glass matrix is the formation of $AlPO_4$ compounds, which allows higher ytterbium doping levels while keeping the core-cladding refractive index difference to a minimum.

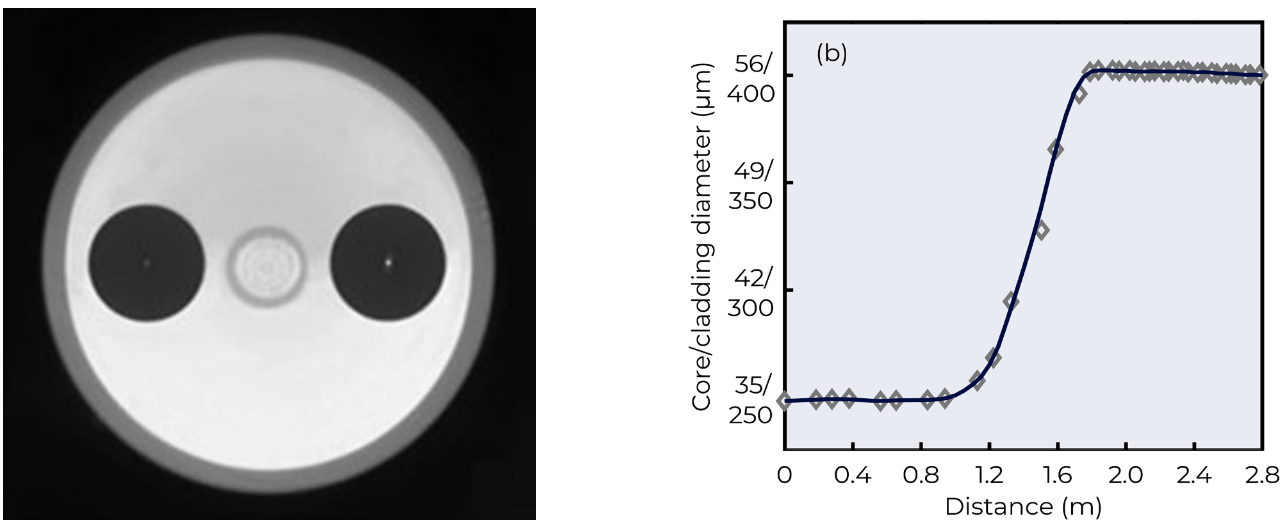

Fig. 1 – (a) Optical micrograph of the 56/400 µm section of the tapered fiber and (b) measured core/cladding diameters (straight line) and calculated effective mode area (dashed line) along the tapered optical fiber.

Table 1: Detailed specifications of the FastFBR
Yb-MCOF-35/250-56/400-07-2.5-T0.8-PM

Optical Properties	
Core NA	0.07 ± 0.01
Cladding NA	> 0.47
Pump guide absorption at 915 nm	2.5 ± 0.5 dB/m
Nominal pump guide absorption at 975 nm	10 dB/m
Birefringence	≥ 1.4×10^{-4}
Beam quality factor M^2	< 1.2
Physical Properties	
Taper length	0.8 ± 0.2 m
Non-tapered sections length	> 1.2 m
Small core diameter	35 ± 3 µm
Small cladding diameter	250 ± 10 µm
Small coating diameter	500 ± 30 µm
Large core diameter	56 ± 5 µm
Large cladding diameter	400 ± 20µm
Large coating diameter	520 ± 30µm
Confined core	Yes
Depressed cladding	Yes

Triple-clad design with depressed cladding and confined core

One key aspect of the INO tapered optical fiber is the use of the patented depressed-cladding technology [1, 2], which consists of a region around the core having a lowered refractive index compared to that of the fiber's raised-index 1st cladding (see Fig. 2). The purpose of this depressed-cladding is to enhance the differential bending losses between LP_{01} and the HOMs by taking advantage of the fact that the evanescent field of HOMs extends further than that of the fundamental mode. By carefully engineering the depth and thickness of the depressed cladding, it is possible to ensure that the fundamental mode remains well confined in the core in a coiled fiber, while the evanescent field of the HOMs reaches the outer cladding region, thus reducing the effective numerical aperture of the HOMs.

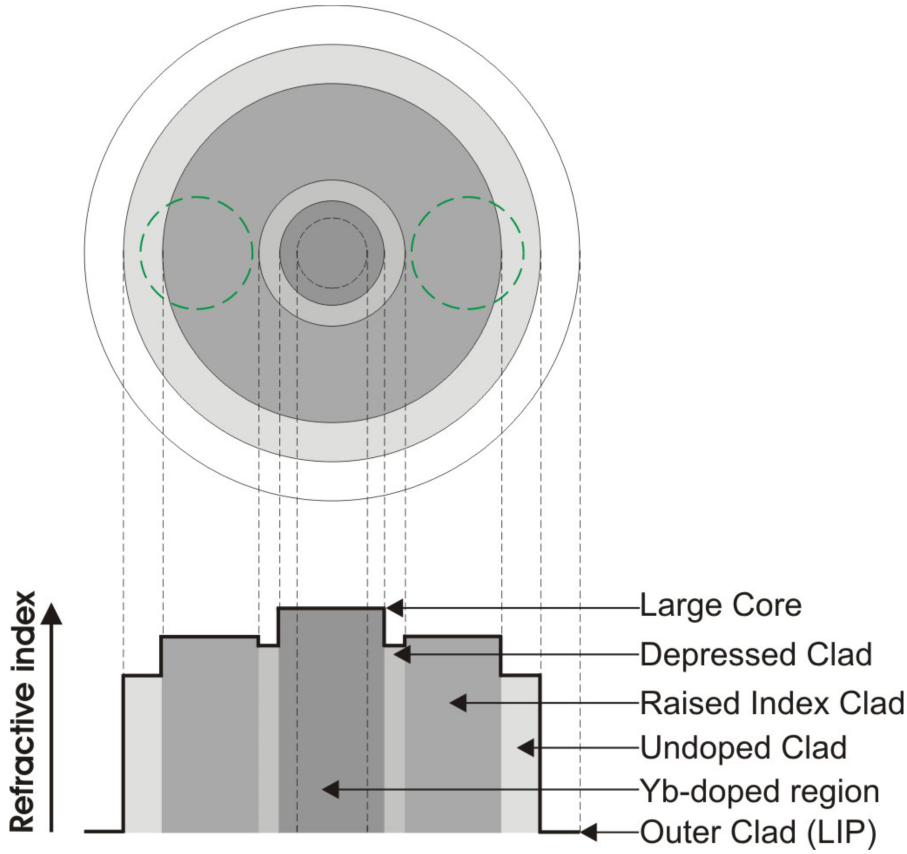

Fig. 2 – Schematic representation of the refractive index profile of a multiclad optical fiber featuring a depressed cladding and confined core.

As it can be seen on Fig. 3(a), coiling the 35/250 section of the fiber taper to a diameter of ~14-16cm leads to differential bending losses of ~10dB/m between LP_{01} and LP_{11}. As it can been seen in Fig. 3(b), the same 14-16cm coiling diameter for the 35/250 sections leads to an effective mode area reduction of the order of ~10% due to bend-induced distortion, which is quite acceptable.

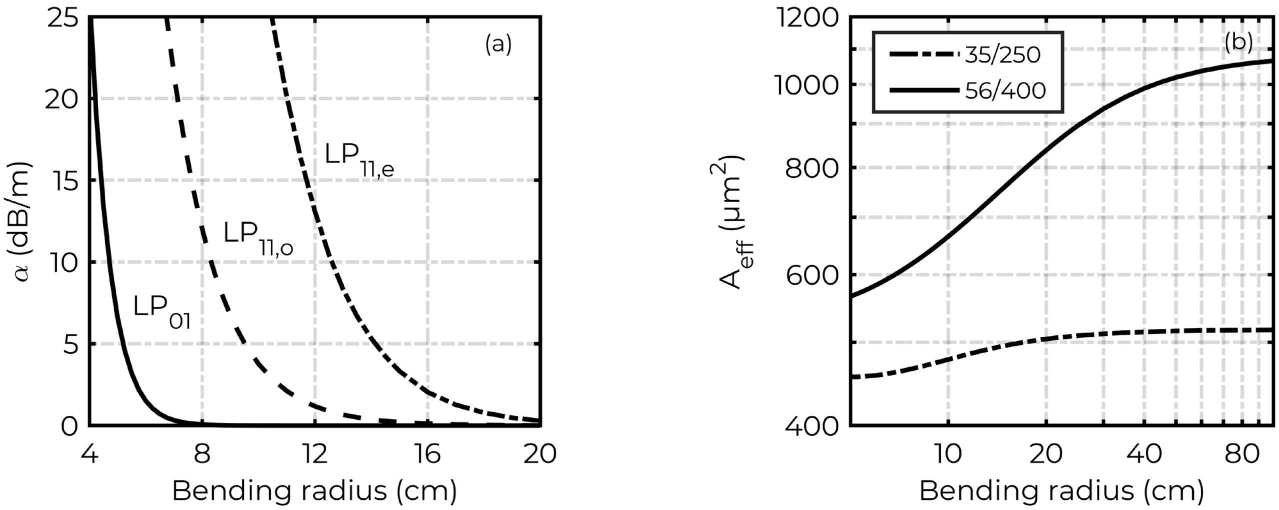

Fig. 3 – (a) Bend-induced propagation losses for the 35/250 μm section of the tapered fiber and (b) effective mode area of LP01 mode for both 35/250 and 56/400 μm sections of the LMA tapered fiber as a function of the bending radius.

Another feature of the INO tapered optical fiber helpful to improve the mode quality is the use of a confined core, which consists of a GeO_2-doped silica outer ring in the fiber's core having the same NA as the active region [3]. The confined core is represented by the dotted lines inside the core on Fig. 2. The purpose of this confined core design is to enhance the overlap of the fundamental mode with the gain compared to that of the HOM's, thus providing better amplification for the fundamental mode and helping maintaining a good mode quality along the length of the fiber. In INO's tapered optical fiber, the confinement factor of Yb dopants in the core is optimised to 2/3 of the core's diameter, which corresponds to ~50% of the core's surface.

Tapered optical fiber packaging

Due to its variable diameter along its length, special attention must be devoted to the packaging of the tapered optical fiber.

As it can be seen on Fig. 3, the optimal coiling diameter of the 35/250 section is in the 14-16cm range, but coiling the 56/400 section down to such a small diameter would lead to severe bend-induced mode distortion and reduce the effective mode area by ~40%. As a result, the packaging layout of the INO tapered optical fiber must be performed according to certain guidelines (see Fig. 4):

1. **35/250 section**: In order to ensure an optimal filtering of the higher-order modes, it is recommended to use **0.5 to 1.0 m** (1 to 2 coil) of 35/250 **fiber coiled to a 14 cm diameter**. This step is crucial to ensure that only the fundamental mode is amplified in the tapered and 56/400 sections.

2. **Tapered section:** It is critical to uncoil the tapered section **gradually** from a 14 cm coiling diameter to a 40 cm coiling diameter over the 0.8 m length of the tapered fiber. Any tight bends, stress points and torsion should be avoided in the tapered section in order to preserve the mode quality.

3. **56/400 section**: In order to avoid bend-induced mode area reduction and losses, it is recommended to keep the 56/400 section at **a coiling diameter larger than 40 cm.** The optimal length to use for the 56/400 section is generally ~0.5-0.7m, so that the total fiber length is in the 2.0 to 2.3m. Like the tapered section, any tight bends, stress points and torsion should be avoided in the 56/400 section in order to preserve the mode quality.

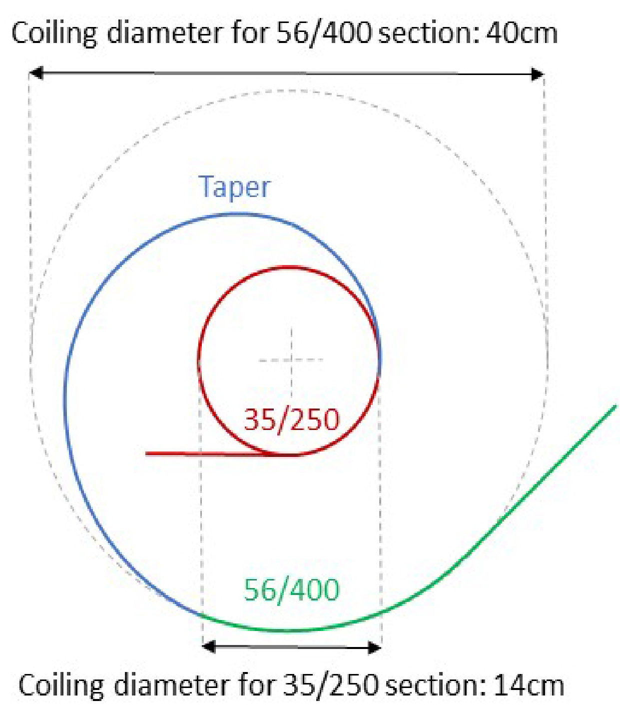

Fig. 4 – Schematic representation of the recommended tapered fiber uncoiling layout for optimal performances

Tapered optical fiber performances

Mode quality

As described in Section 2, the INO tapered optical fiber uses a multiclad fiber design, which includes a depressed cladding and a confined core in order to help obtaining an optimal mode quality. In this section, we will present experimental results showing the typical mode quality one can expect from the tapered fiber packaged according to the guidelines described above.

A schematic representation of the experimental setup is presented in Fig. 5. The taper has been tested as a power amplifier in a counter-pumping scheme with the pump and signal light free-space coupled. Note that this pumping scheme is not mandatory and co-pumping or dual-pumping are also acceptable. It is also worth noting that free space coupling for the signal has only been used for the tapered fiber baseline characterization and to measure the residual pump power. To take full advantage of the benefits of the tapered fiber, it is recommended to splice the taper input to a fiber or pump combiner and fit the output with an endcap.

The tapered fiber has been tested using a narrow-linewidth 1064 nm seed laser with 0.5W average power and 976nm pump light from wavelength-stabilized laser diodes (200µm – 0.22NA). Non-tapered fiber sections of about 0.8m and 0.5m (for the 35/250 and 56/400, respectively) were used on both side of the tapered section, resulting in a total length of ~2.1m. An average power of more than 200W has been obtained, with a slope efficiency of ~84% (Fig. 6). A polarization extinction ratio (PER) greater than 18dB has been obtained over the complete power range with the seed polarization aligned along the slow axis of the fiber. As shown on Fig. 6 as well, a near diffraction-limited output was obtained, with a measured $M^2<1.2$ for both x and y axis over the whole power range in this test, demonstrating that the INO tapered optical fiber is capable of generating a high average power and high beam quality from its 1000 μm^2 output. It should be noted that the M^2 value presented on Fig. 6 is slightly overestimated due to inaccurate beam diameter evaluation near the waist location attributable to thermal blooming on the CCD silicon detector used for the spot size evaluation (D4σ method). The resulting overestimation of the spot size then translates into an overestimation of the M^2 value shown on Fig. 6.

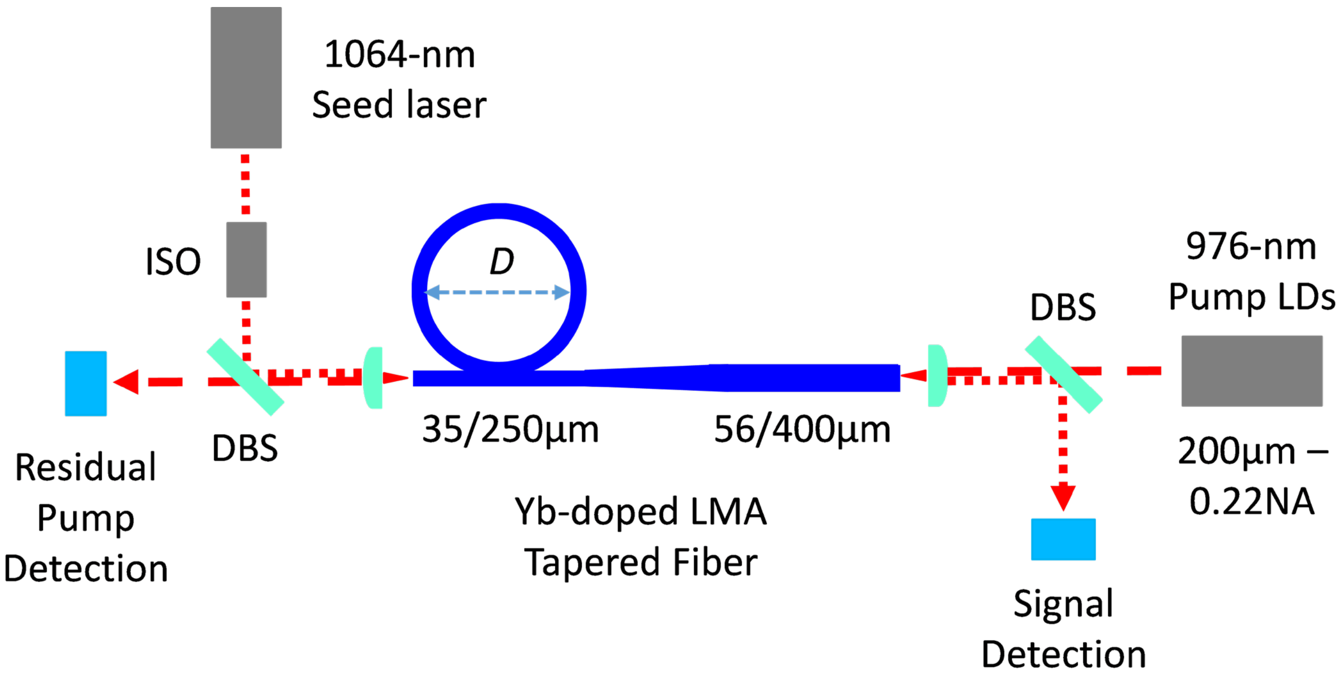

Fig. 5 – Schematic representation of the experimental setup used for tapered fiber efficiency and beam quality measurement.

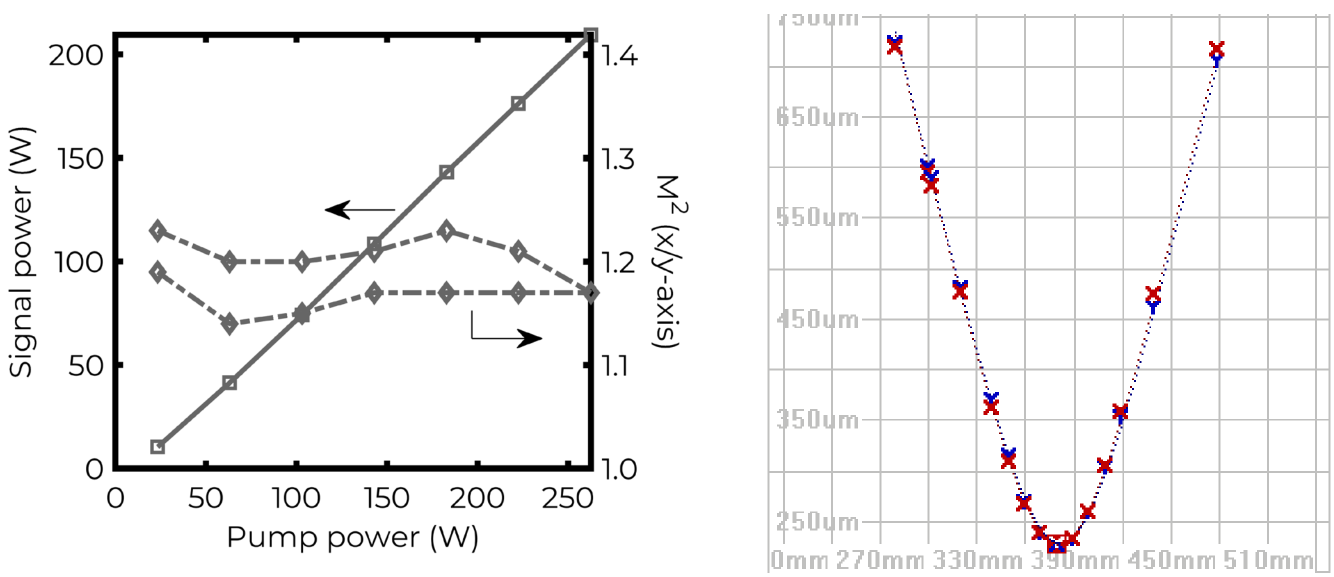

Fig. 6 – Measured M² and signal power as a function of the pump power at the tapered optical fiber output (left). Typical laser caustic obtained at the tapered fiber output for the M² measurement performed using an Ophir-Spiricon M²-200s beam propagation analyzer (right).

Conclusion

This white paper has presented the characteristics and the good operational practices for the INO FastFBR polarization-maintaining tapered optical fiber. Due to its longitudinal profile, this 35/250 to 56/400 tapered fiber allows a 1000 μm^2 effective area output while retaining the convenience and mode-filtering properties of smaller core LMA fibers. It is thus best suited for pulsed amplifier applications requiring an all-fiber package and high output power.

References

[1] Roy *et al.*, “Yb-doped large mode area fibers with depressed clad and dopant confinement,” Proc. SPIE 9728, Fiber Lasers XIII: Technology, Systems, and Applications, 97281W (April 5, 2016).
[2] Paré *et al.*, “Multi-cladding fiber”, US Patent 8,731,358 B2
[3] Laperle *et al.*, “Yb-doped LMA triple-clad fiber for power amplifiers,” Proc. SPIE 6453, Fiber Lasers IV: Technology, Systems, and Applications, 645308 (February 21, 2007).

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