Design considerations for large-mode-area polarization maintaining double clad fibers

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ABSTRACT

Large-mode-area double clad fibers offer excellent efficiency and beam quality, high output power as well as lightweight, robust and reliable packaging. The addition of polarization maintaining property though use of well-know Panda-structure has further increased the interest in double clad fibers, especially in fibers doped with ytterbium (Yb). Many material processing, military and R&D applications benefit from wavelength conversion by nonlinear effects, from IR through UV, of 1064nm Q-switched pulses through polarization maintaining large-mode-area double clad Yb-fiber amplifiers. The possibility of power scaling through coherent beam combining has also been identified by the military. The design of a polarization maintaining large modea area double clad fiber for the above mentioned applications must address several key performance parameters: provide large mode area (>300μm^2), high efficiency (>80% slope PCE), high average power (>100W), high birefringence (>2*10-4) and offer good beam quality (M^2 <1.5), short fiber length (<3m), as well as high reliability and good usability. Further optimization of the fiber design must take into consideration the impairment of the fiber by thermal loading as well as coiling of the fiber for elimination of higher order modes. This paper presents the key design considerations of such fibers for high-average-power pulsed amplifiers and provides the latest experimental techniques to verify the results. The design and results on high performance highly Yb-doped polarization maintaining large mode area fiber manufactured by the Direct Nanoparticle Deposition technology are presented and possibilities and opportunities brought by this technology are discussed.

Keywords: Polarization maintaining, Ytterbium, Double cladding, Fiber amplifier, Fiber laser

1. INTRODUCTION

Advances in design and manufacturing of highly-doped ytterbium double cladding (DC) fibers have enabled the realization of high-average-power diffraction-limited fiber amplifiers reaching mJ pulse energies and MW peak powers, as well as continuous wave fiber lasers exceeding 1kW output powers with nearly single-mode output beams [1]. Many of the applications requiring such high peak and CW powers eventually require a polarization maintaining (PM) double clad fiber. Typical such application is wavelength conversion thorough nonlinear effect in a crystal, requiring high-peak-power polarized source for efficient conversion. There is also increasing interest for coherently combining kW level fiber lasers to greater than 10kW outputs for industrial and military applications, again requiring a PM double clad fiber for reaching this goal.

First reported polarization maintaining double clad fiber amplifier employed a bow-tie active fiber [2]. As bow-tie type PM fiber has substantial limitations in terms of manufacturability and scalability, PM double clad fiber was soon thereafter proposed to be made based on the well-know Panda type of PM fiber [3]. Panda PM preforms have the advantage of effectively decoupling the fabrication of the preform and the stress elements, as well as opening the possibility to make large PM preforms and so scale-up production volumes. This paper presents the key design considerations for fabrication and use of large-mode area (LMA) polarization maintaining double clad fiber based on the Panda type of PM fiber.

2. DESIGN CONSIDERATIONS

2.1. The PM-LMA fiber design

The PM-LMA fiber core and cladding design needs to address the issues of achieving as large a core as possible while maintaining diffraction-limited beam quality, and to provide high enough pump absorption for application lengths of several meters or shorter to minimize non-linear effects. With these considerations in mind, scaling of fiber lasers to mJ pulse energies and MW peak powers should be feasible. A low numerical aperture 30µm core has been demonstrated to provide diffraction-limited output and high extracted pulse energy together with very high cladding absorption in 250µm octagonal shaped fiber, enabling short application length of just 1-2 meters [4]. The same fiber geometry (30/250) and recipe (0.07 NA core with ~1200dB/m peak material absorption) was selected for the PM-LMA development fiber.

2.2. Positioning the stress rods

Design target was to achieve birefringence $>2\cdot10^{-4}$ and polarization extinction ratio >20dB in a 1m long 30/250 type fiber. It is believed that these values are sufficient to qualify the fiber for majority of polarization maintaining active fiber applications.

An analytic model [5] was used to estimate the required thermal expansion coefficient and thus B2O3 content of the stress rods, as well as to determine the optimal positioning and size of the rods. The design target for positioning the stress elements was to provide high birefringence without compromising the fiber performance or decreasing the manufacturing yield of the fiber. The performance of the fiber may be compromized by placing the stress rods too close to the core so as to cause scattering loss to the signal light propagating in the core, or by using lossy rods which will absorb or scatter the pump light propagating in the cladding. The stress rods must be set apart from the outer side of the cladding so as not to relax the stresses. Too large or poorly positioned rods may also cause reduction in fiber yield and performance through poor geometry control during the drawing of the fiber.

Three parameters that effect the birefringence are B_2O_3 content of the stress rods (ρ_{B2O3}), ratio of the stress rod diameter to the cladding radius (t/b) and the distance from the core center to the rod (r). These parameters are illustrated in figure 1. Figure 2 shows the geometry of the actual fabricated 30/250 PM-LMA fiber.

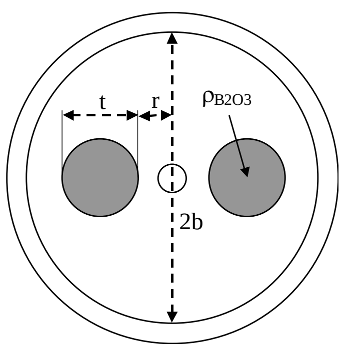

Figure 1. Cross-section of Panda-type PM fiber

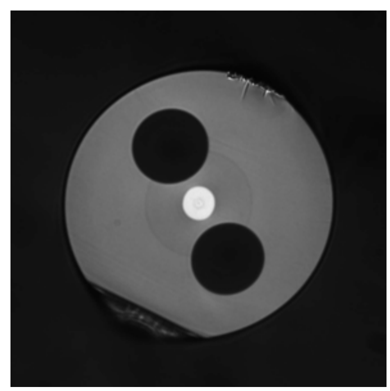

Figure 2. Cross-section of fabricated 30/250 PM-LMA fiber (round cladding deformed in cleaving)

Starting point for B_2O_3 concentration was availability of good quality stress rods with 15±1 mol% of B_2O_3. Several experimental fibers were first desinged and manutactured using these rods. One particular fiber (shown in figure 2) was designed so as to place the rods close to the core edge, only some 7µm away, to experimentally determine if the proximity of the rods to the core induced degradation of fiber performance. Further, the stress rod diameter was designed to be very large (t/b of 0.6). High birefringence of $3.1\cdot10^{-4} \pm 0.3\cdot10^{-4}$ was measured for the fiber (measurement discussed and shown in section 3.3), comparing well with the modeled result of $3.05\cdot10^{-4}$ (15mol% B_2O_3 stress rods assumed). This extreme design may be optimized by moving the rods further away from the core to leave safe marging of 15µm bridge in between the rod and core edge, and by using optimal rod diameter of t = 56µm. The resulting birefringence is expected to be $3.5\cdot10^{-4}$.

2.3. Thermal considerations

In optimizing the PM-LMA fiber for high-average-power pulsed applications with very short application fiber lengths of few meters, the issue of thermal loading needs to be properly addressed. Fiber temperature of roughly 330°C was calculated for a 50m long fiber with 4.6µm core and 300µm cladding diameter pumped with 180W at 915nm [6]. This result can be scaled to the 30/250 geometry fiber, by assuming single-end pumping using 6 + 1 multimode pump combiner with 6 x 30 W = 180W launced pump power. Using pump wavelength of 976nm, complete pump absorption can be expected in 1 meter long fiber. Using equations of reference [6], average fiber temperatures of 46°C and 2043°C are estimated depending on the convection coefficient. The extreme temperature of 2043°C assumes convection coefficient of 0.001 $Wcm^{-2}K^{-1}$ representing air-cooled fiber without convection. The average temperature of 46°C is estimated for convection coefficient 0.1 $Wcm^{-2}K^{-1}$, representing forced air-cooling. Temperature gradient within the fiber is smaller than 10°C in both cases. The ambient air temperature was presumed to be 298K.

The passively air-cooled system does not allow the use of high pump power. The coating material usually can in long term withstand only about 100°C. The fiber needs to be thermally coupled to cooling element that is actively cooled for example with water or forced air. The thermal coupling can be made using elastic materials that prevent the formation of stress between the fiber and the cooling system, which may potentially lead to undesired polarization performance or at extreme, fiber breakage. High temperature coating materials should be considered for added reliability in applications, where fiber cooling has to be compromised due to cost, packaging or other limitations.

3. FIBER CHARACTERIZATION

3.1. Cladding absorption

Cladding absorption at 920nm was first measured with cut-back method using a white light source (WLS) with 1m and 0.5m long pieces of fiber. Secondly the absorption was measured by pumping a 3m long fiber and measuring the ratio of coupled pump power to transmitted, unabsorbed pump power. The results were similar, namely the WLS method gave 4.1dB/m of cladding absorption, and the pump laser method gave 4.2dB/m.

To confirm that the low index stress rods are providing sufficient mode mixing, comparison between commonly used octagonal shaped double cladding fiber of the same dimension and the PM-LMA double cladding fiber was made. Again, light from 920nm pump laser was launched to the fibers and a cut-back measurement from 8m down to several tens of centimeters was done. Two measurements and cleaves were taken at each fiber length to reduce the measured power uncertainty due to cleaving. Figure 3 shows the measured normalized pump transmission in the two types of double clad fibers.

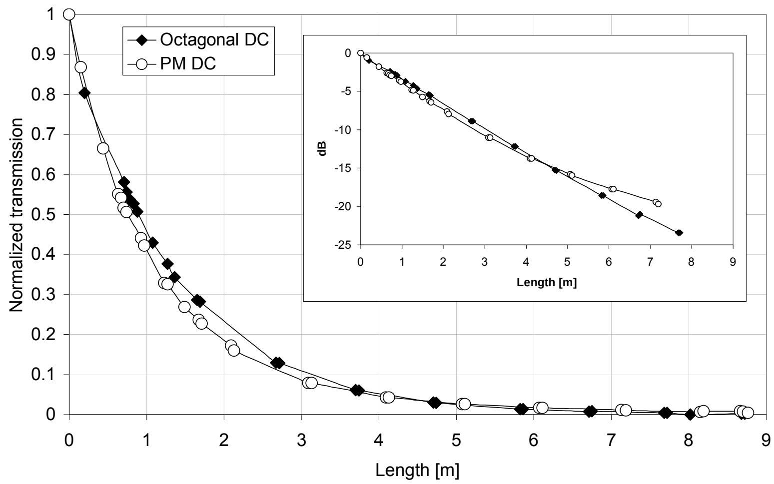

Figure 3. Cladding absorption in octagonal shaped and panda-type PM-LMA double clad fiber versus fiber length.

This measurement confirms that a round Panda-type PM-LMA double cladding fiber provides good cladding absorption through pump mode mixing in the low index stress rods. Up to 4 meters, the pump absorption is actually better in PM double clad fiber than in the octagonal DC fiber, when pump light is launched from a fiber where the power is uniformly spread to all of the modes. The inset graph shows the logarithm of the transmission, giving better view of the cladding absorption at longer fiber lengths. The cross-point between the two types of double clad fibers is at ~4m for this particular fiber geometry. This is probably due to pump modes travelling mainly outside of the stress rods. At fiber lengths longer than 4m, the octagonal shape is again more efficient in maintaining cladding absorption. This is not a concern for the selected fiber type, because usually the required pump absorption is <20dB.

3.2. Slope efficiency

The slope efficiency of 30/250 PM-LMA fiber was measured using the setup described in figure 4. Pump laser with a maximum output power of 300W at 971nm was launched from 400µm fiber with 0.22 NA through collimating and focusing optics onto the cleaved end of the 250µm fiber. Laser cavity was formed by the cleaved fiber end and a fully reflecting mirror placed at the other end of the active fiber. Output power was measured through dichroic filter placed in between the focusing lens and the active fiber. The fiber sample was prepared by pre-cutting it to roughly 13dB total absorption length, straight cleaving the fiber ends and placing the pump coupling end into an aluminium chuck designed to remove heat from the fiber end. The fiber was coiled first to a 80mm and then to a 60mm coil. The smaller 60mm coiling diameter was selected because it is believed to provide sufficient discrimination for the higher order modes in an amplifier configuration using the coiling method [7]. However, no beam quality measurements were done for the fiber, only the effect of coiling to the slope efficiency was measured.

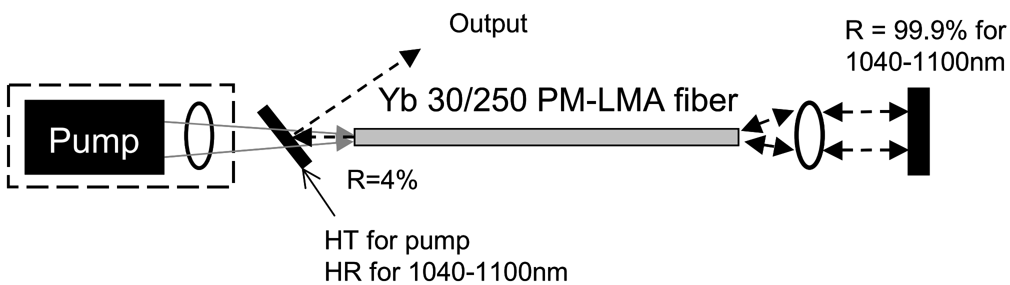

Figure 4. Experimental Yb-fiber laser measurement arrangement. HT: High-transmission, HR: High reflectivity.

Figure 5 shows the laser output power as a function of estimated coupled power for fiber for the 80mm and 60mm coils. A cut-back measurement indicated that roughly 60% of the pump power was launched into the fiber. A slope power conversion efficiency of 77% was determined from the measured laser output power for both coiling radius. Larger threshold power seen when fiber was coiled to 60mm is mainly attributed to worse laser cavity caused by poor cleave or alignment of fully reflective mirror. Because the available pump wavelength was somewhat offset from the ytterbium peak absorption at 976nm, and because there was no means to monitor the pump laser wavelength during measurements, the fiber length was sub-optimal. Coupled pump power was limited to roughly 30W. Above this power, overheating of the fiber occurred at the pump coupling end of the fiber and caused the coating to be damaged.

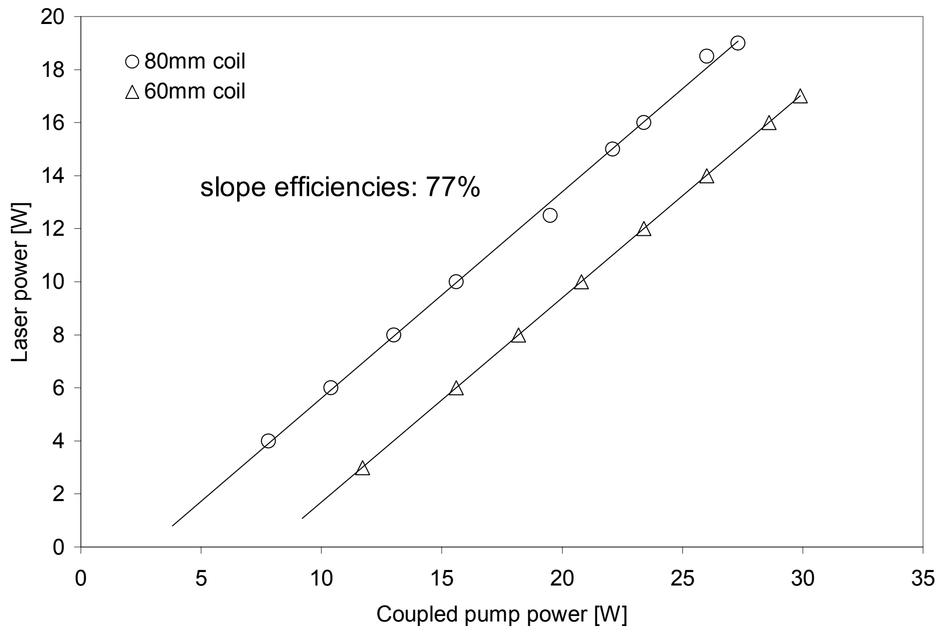

Figure 5. Measured laser output power as the function of coupled pump power for 60mm and 80mm fiber coiling radius.

3.3. Birefringence and polarization extinction ratio

A broadband randomly polarized ASE source at 1.55µm was used as the light source for polarization extinction ratio (PER) and birefringence measurements. A free-space linear polarizer was used to polarize the coupled light. Another polarizer was used at the output end, as shown in figure 6. The two linear polarizers used in the setup had a combined PER of >28dB, which was measured by substituting the optical spectrum analyzer (OSA) with a power meter. The use of 1.55µm wavelength for measuring Yb-doped PM-LMA fibers has two advantages, namely the absence of active ion absorption giving a larger dynamic range for the measurement, and the lower V-number of the fiber, resulting in fewer modes and reduced noise from the modal beating.

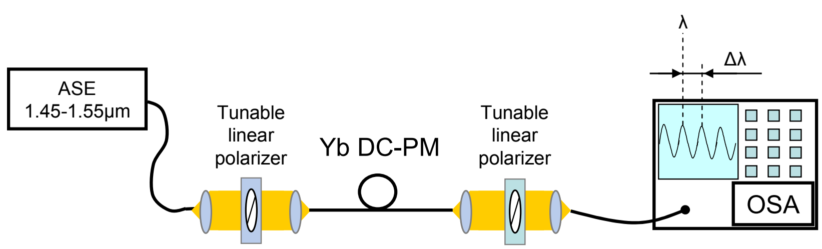

Figure 6. Measurement setup used for the PER and birefringence measurement.

The PER of the Yb-doped PM-LMA fiber was measured first. This measurement also provided means to find and align the fiber birefringence (slow) axis for the birefringence measurement. The fiber was first inspected under microscope to prealign the birefringence axis in relation to the source axis. The output polarizer was then rotated to find the maximum and minimum transmitted power, with PER given by

$$PER = 10 \cdot \log_{10}(P_{slow} / P_{fast}) dB ,$$

where P_{slow} and P_{fast} are the maximum and minimum measured output power, respectively. Several iterations of tuning the input and output polarizers were needed in order to minimize the error due to misalignment of polarization axis.

In the birefringence measurement the linearly polarized source was launched into the core of the PM-LMA fiber with the polarization direction oriented in the middle of the slow and fast polarization axis. The input polarizer was turned 45 degrees from the slow axis position found in PER measurement with roughly ±2 degrees accuracy. Output light from the fiber was passed though the latter polarizer oriented in the same angle as the input end. Wavelength-dependent beats were recorded using a spectrum analyser and birefringence was calculated by fitting a sinusoidal function to the beat spectrum.

The PM fibers in question have multimodal cores, and the core is surrounded by a cladding where light propagation is nearly lossless. The multiple modes in the core cause modal beating to the measured spectra, and the light propagating in the cladding is detrimental to both the measurement of PER and birefringence. To this end, the coiling radius was tuned to provide extra loss for the higher order modes. To remove cladding modes, fibers were stripped from both ends and index matching gel was applied, thus effective filtering out modes propagating in the cladding. A multimode fiber was used to collect the light from the setup to the OSA. Finally, a mode beat spectrum was measured with both of the polarizers tuned to the slow polarization axis. The mode beat spectrum was reduced from the birefringence beat spectrum in order to reduce the modal beat noise of the result.

A 1m long piece of the 30/250 PM-LMA fiber was prepared as described above. Polarization extinction ratio of >25 dB was measured from the fiber. Figure 7 shows the beat spectrum result and a sinusoidal fitting function. The beat length and it's tolerance were determined from the fit, and the measured birefringence was $3.1 \cdot 10^{-4} \pm 0.3 \cdot 10^{-4}$.

It can be deduced from the depth of the beating that most of the measured power was in the fundamental mode, therefore sufficient filtering of the higher order modes was achieved.

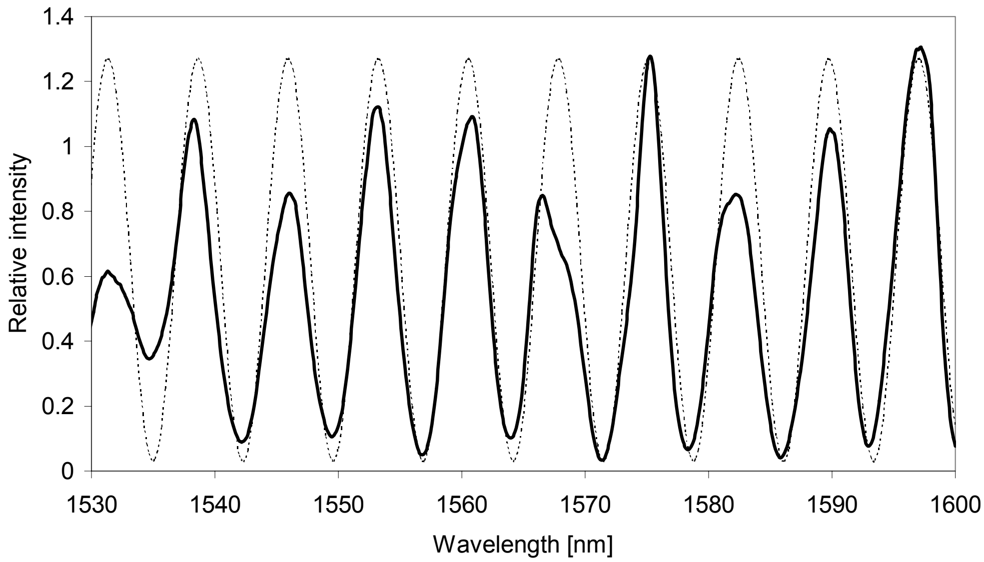

Figure 7. Measured beat spectrum from a 1m long piece of the 30/250 PM-LMA fiber and the sinusoidal fit, giving a birefringence of $3.1 \cdot 10^{-4} \pm 0.3 \cdot 10^{-4}$.

4. LEVERAGING THE DIRECT NANOPARTICLE DEPOSITION TECHNOLOGY

Liekki Direct Nanoparticle Deposition (DND) technology offers several advantages in making PM-LMA fibers compared to conventional fiber manufacturing technologies such as MCVD and solution doping. The DND core rod growth is a single-step manufacturing process that facilitates the scaling-up of the preform size. The large uniformly doped core rods enable the scaling-up of the whole PM-LMA double clad fiber manufacturing process. First advantage of this comes from larger diameter preforms in which large and deeper holes can be drilled for the stress rods. The larger diameter results better quality hole surfaces and lower manufacturing cost per drawn fiber meter. Secondly large preforms and long fiber draws also drive better fiber quality. Core rods up to 7mm in diameter have been manufactured so far, with potential in making ~60mm diameter preforms for the 30/250 geometry.

DND technology also makes it possible to exceed the core or MFD size of the current state-of-the-art diffraction-limited 30µm step-index large mode area fibers by gradient doping of active ions and/or refractive index constituents in a larger core. A DND core rod typically consists of several hundreds of layers, each tens of micrometers thin, thus giving excellent control over the refractive index and doping profile. Lastly, one of the greatest advantages of Panda-type PM fiber is that one can decouple in the fabrication phase the optimization of the stress elements and the preform. With DND technology, also the core design and optimization can be decoupled, opening up possibilities to completely new ways of designing and making polarization maintaining LMA fibers.

5. CONCLUSIONS

High birefringence ($>2 \cdot 10^{-4}$) can be achieved in large-mode area double cladding fibers using stress rods doped with 15±1 mol% of B_2O_3. Birefringence of $3.1 \cdot 10^{-4}$ (corresponding to beat length of 3.4mm at 1060nm), was reached by placing stress rods within 7µm of the core without seeing detrimental effects on the slope conversion efficiency. However, more rigorous analysis needs to be done to verify the results. The design may be further optimized by moving the rods further away from the core to leave safe marging of 15µm in between the core and stress rods and by using optimal stress rods diameter of 56µm. Birefringence level of $3.5 \cdot 10^{-4}$ is then expected to be reached.

In addition to high birefringence, the manufactured 30/250 type PM-LMA fiber featured good polarization extinction of >25dB, cladding absorption of 4.1dB/m at 920nm and slope efficiency of 77% (at 971nm pump wavelength). The round PM double clad fiber was found to provide efficient pump absorption when compared to conventional double clad octagonal shaped fiber of the same dimensions. This is attributed to effective pump light mode mixing due to the low index stress elements in the configuration acting as mode scramblers. Absorption of >15dB/m can be expected at 978nm pumping, enabling very short application lengths of 1m or less and greatly increased threshold for non-linear effects. Proper management of thermal loading will enable this fiber to attain mJ level pulse energies and MW peak powers.

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