The road to kiloWatt fiber lasers

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ABSTRACT

Although fiber amplifiers have been employed in communications systems for many years, until very recently the fiber laser was little more than a scientific curiosity. However the fiber laser format has a number of intrinsic advantages over lamp and diode pumped YAG lasers including size, reliability, wavelength selectivity, heat dissipation, wallplug efficiency and operational cost; and with kiloWatt output powers now possible fiber lasers are beginning to replace lamp and diode pumped YAG lasers in many industrial applications. In this paper we review the recent and ongoing advances in fiber design that have facilitated this revolution.

Keywords: Double Clad (DC) fibers, Large Mode Area (LMA) fiber, Fiber laser.

1. INTRODUCTION

The lanthanide-doped glass fiber laser was invented by Elias Snitzer in the 1960's [1, 2, 3] however the total achievable output power of these devices was ultimately limited by the need to launch excitation energy directly into the core of the fiber. These devices typically generated only 10's to 100's of mW's, making them significantly inferior to their Nd:YAG and gas laser alternative technologies. However with the advent of cladding pump fiber designs in 1988 [4] this limitation was removed and in 1999 high power fiber lasers became a reality, with the world's first single-mode fiber laser exhibiting in excess of 100W cw output [5]. By negating the requirement for excitation energy to be coupled directly into the relatively small single-mode core it was now possible to employ low-cost, large-area (multi-mode), high-power semiconductor pump sources. However it was soon recognized that conventional small core, high NA fiber designs were not appropriate to applications requiring further scaling of the output power [6]. More specifically it was found that the maximum achievable output power in such fibers were restricted by a fundamental susceptibility to optical nonlinearities, including stimulated Raman scattering (SRS), stimulated Brillouin scattering (SBS) and self-phase modulation. In order to overcome the limitations imposed by these parasitic nonlinear processes, it has been necessary to develop fibers with high rare-earth dopant concentrations in relatively large core, low numerical aperture fibers. These so-called large mode area (LMA) fibers are directly responsible for the recent explosion in demonstrated diffraction-limited beam quality high output powers, now approaching the kW-level from a single fiber [7,8,9].

To further scale the output power it is necessary to combine the output of several fiber lasers. Indeed, for a number of industrial and military applications it is desirable to scale the total output power to between several and hundreds of kW's. It is therefore advantageous to be able to combine the beams from multiple fibers and this in turn makes it desirable for the fiber to also be polarization maintaining. This provides yet another layer of complexity to the fiber design but such fibers are now a commercial reality [10] and we will discuss the various criteria that are critical for designing these PM double clad fibers.

2. LARGE MODE AREA (LMA) YTTERBIUM-DOPED FIBERS

For certain applications, such as ranging and free-space communications, operating in the "eye-safe" 1.5-2.0micron range is preferred. In addition there are a number of sensing and medical applications that require other specific wavelengths. For such "wavelength specific" applications it becomes necessary to employ a variety of optically-active lanthanide ions, such as neodymium, thulium or codoped erbium/ytterbium. However for non-wavelength specific applications, requiring only extremely high output powers a number of unique advantages have made ytterbium the dopant of choice. More specifically ytterbium-doped fibers offer high output powers tunable over a broad range of wavelengths, from around 975-1200nm (typically around 1060nm) [11]. Ytterbium also has a relatively small quantum defect, that is to say because the pump wavelength (typically 915-975nm) is close to the lasing wavelength very little energy is lost to heating. Furthermore, unlike other lanthanide ions ytterbium has only a single excited state and thereby is not subject to complications arising from excited state absorption (ESA) and is relatively immune to self-quenching processes. Consequently high concentrations of ytterbium ions can be incorporated while maintaining excellent conversion efficiencies (typically greater than 75%). For this reason the industry has focused on the development of ytterbium doped fibers and the following discussion will deal primarily with these fiber designs. It should be noted however that neodymium/ytterbium-codoped fibers have demonstrated power scaling advantages by virtue of the fact that they increase the options for wavelength multiplexing the pump diodes (the neodymium has a peak absorption around 810nm and gain peak around 1060nm) [9].

Naturally it is possible to ensure diffraction-limited beam quality from a single-mode core in a double clad fiber geometry. Unfortunately such a design also limits the total achievable output power and in pulsed laser devices the average power, peak power and pulse energy. These limitations are the result of low energy storage (for pulsed applications) and the effects of parasitic nonlinear processes. The energy storage capacity is determined by a combination of the number of active species present and the maximum achievable population inversion, which is in turn determined by the likelihood of amplified spontaneous emission (ASE) [12]. In order to overcome these limitations it has been necessary to develop highly-doped, large mode area (LMA) fibers. By increasing the core diameter of a fiber and reducing NA it is possible to maintain single-mode operation whilst both reducing the fraction of spontaneous emission captured by the core and decreasing the power density in the fiber, thereby increasing the threshold power for the nonlinear processes. Furthermore the total number of active ions present, and so the energy storage capacity, increases as the square of the core diameter (for a given glass dopant concentration and cladding diameter). Consequently it is possible to reduce the length of the fiber device thereby further increasing the threshold for the nonlinear processes.

Of course there is an upper limit to the core diameter beyond which single-mode operation is not guaranteed. More specifically for a step-index fiber it is known that single-mode operation requires that the V-value remains below 2.405, where V is proportional to the core diameter (d_{core}) and numerical aperture (NA_{core}) and inversely proportional to the wavelength of operation (l) [13]:

$$V = \frac{p d_{core} NA_{core}}{l} \qquad (1).$$

At very low NA's (below around 0.06) fibers begin to exhibit extremely high bend sensitivity. This imposes a practical lower limit on NA and hence an upper limit on core diameter. Fortunately however there are a number of techniques for the suppression of higher-order lasing modes that allow us to use even larger core diameters, wherein essentially multimoded fibers can be made to operate with a diffraction limited beam quality. These techniques include suitably manipulating the fiber index and dopant profiles [14, 15]; using special cavity configurations [16]; tapering the fiber ends [17] ; adjusting the seed launch conditions [18] ; and coiling the fiber to induce substantial bend loss for all transverse modes other than the fundamental [19]. Perhaps the simplest and least expensive of all these is the coiling technique, it does not require careful matching of the seed mode and does not rely upon complex fiber designs. It is only necessary to choose the radius of curvature (based upon core diameter and NA) that will discriminate against high-order modes. This technique exploits the fact that the fundamental mode is the least sensitive to bend loss and that the attenuation due to bend loss is exponentially dependant upon the bend radius. For example Fig. 1 shows the bend loss as a function of bend radius for a 0.06NA, 30micron core diameter fiber. Such a fiber in a linear configuration can support around five modes but with the appropriate choice of bend radius (say around 50mm) the LP11 experiences around 50dB/m of attenuation (and higher order modes are even more attenuated) whilst the LP01 mode experiences only around 0.01dB/m. It is important to note that this technique does not involve the stripping of power from higher order modes, but rather the suppression of those modes along the entire fiber length. As such power is not attenuated and the efficiency of the laser device is not markedly reduced.

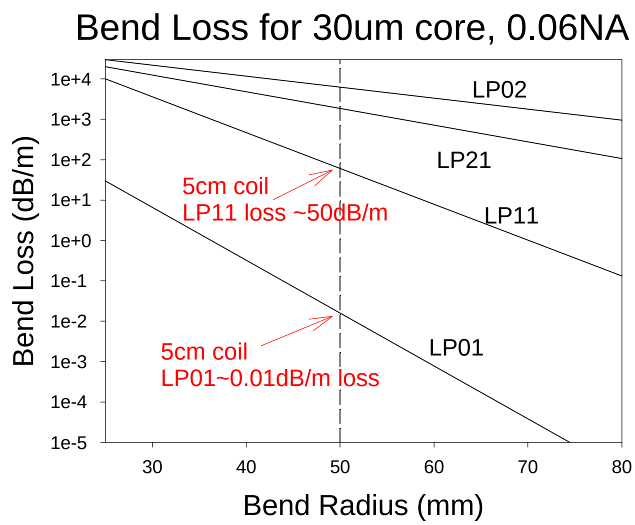


Fig. 1. Bend loss as a function of bend radius for a 0.06NA, 30micron core diameter fiber.

In Fig. 2 we show the measured near-field spatial profile of an ytterbium-doped fiber amplifier with a core diameter of 25micron and an NA of 0.1 when seeded with a cw laser at 1064nm. The profile on the left shows the multimoded (around 27 guided modes) output of the uncoiled fiber and on the right the diffraction-limited (measured M^2 value of 1.08+/-0.03) output of the coiled fiber.

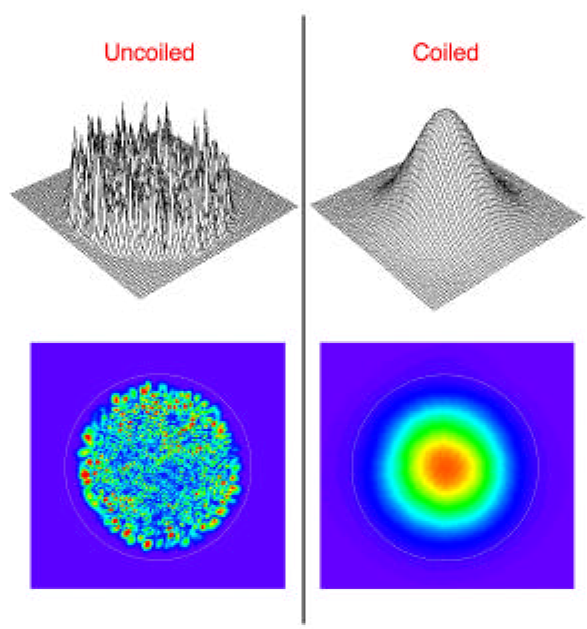


Fig. 2. Measured near-field spatial profile of an ytterbium-doped LMA DCF amplifier in an uncoiled (left) and coiled configuration (right) [20].

3. POWER SCALING – BEAM COMBINING

It is not feasible to indefinitely increase the output power capability of an LMA DCF through scaling of the core diameter. Ultimately there will be some upper limit above which output beam quality will begin to degrade. In order to help overcome this hurdle research is also underway in order to further refine the design of LMA DCF's, through optimizing of the glass composition and waveguiding structure. These include techniques for reducing the peak power density of light propagating in the core, via careful manipulation of the core refractive index profile [21, 22]. The effectiveness of such techniques is however somewhat limited and alternative techniques are required for significant power scaling requirements.

Output powers exceeding 1kW have already been demonstrated in multiplexed fiber devices with poor beam quality [23] and more recently in a single fiber with poor beam quality [8]. However with the growing need for output powers of several kW's for industrial cutting and welding applications and greater than 100 kW's (cw) for military and aerospace applications the current goal of a number of research groups is to achieve diffraction-limited kW powers from a single fiber and then to combine the outputs of several such devices. A number of such power scaling techniques have been demonstrated including coherent beam combining, spectral beam combining and polarization beam combining. For these extremely high-power applications operation under stable linear polarization is becoming a requirement [24, 25]. Furthermore there are a number of other applications requiring PM output including coherent optical communications, nonlinear frequency conversion, pumping optical parametric devices and all manner of mode-locked, Q-switched and narrow linewidth fiber lasers. Consequently there has been an increasing demand for polarization-maintaining double clad fibers (PM-DCF) in recent years.

In the past, different approaches have been suggested to obtain PM operation using non-PM fibers [25, 26]. Such approaches however have their limitations and the preferred technology is to use a truly PM-DCF. Whilst passive polarization maintaining fibers have been commercially available for many years, actively doped PM fibers have not been available until recently [27, 28]. In fact an amplifier employing Yb-doped PM-DCF was first reported by Kliner *et al* [28] in 2000. This fiber was of a bow-tie geometry and although acceptable for proof of concept and research and development, it has substantial limitations in terms of preform manufacturability, uniformity and scalability. Furthermore, the non-ideal refractive index profile inherent to such doped bow-tie fibers (Fig. 3) makes diffraction-limited operation difficult to achieve.

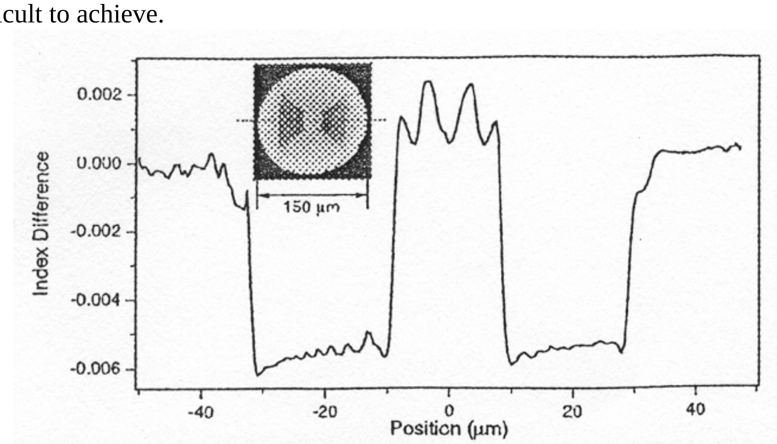


Fig. 3. Refractive index profile and optical image of the non-ideal bow-tie PM-DCF [26].

4. DESIGN, FABRICATION AND CHARACTERISATION OF PM-DCF

4.1. Which PM design is best?

There are three main types of highly birefringent PM fiber, namely elliptical clad, bow-tie and Panda. Fig. 4(a) shows a schematic diagram of the steps involved in making a bow-tie type PM fiber. A high quality synthetic quartz tube serves as a substrate into which several layers of borosilicate glass are deposited. Next the substrate rotation is stopped and using a specialized ribbon burner a region of the borosilicate glass is volatilized. The substrate tube is then rotated by 180 degrees and a similar sector is volatilized. Special care is taken to ensure that the sectors of glass from which the borosilicate glass has been volatilized are diametrically opposite to each other and dimensionally equal. Several layers of glass are further deposited before the Ytterbium-doped core is deposited. These layers act as a buffer between the borosilicate stress members and the core and ensure that the evanescent field does not propagate in the stress elements. The Ytterbium-doped core is deposited using a solution doping technology. The substrate tube with the various layers of deposited glass is then carefully collapsed into a rod. Elliptical clad fiber production is somewhat similar but Panda fiber involves a markedly different process.

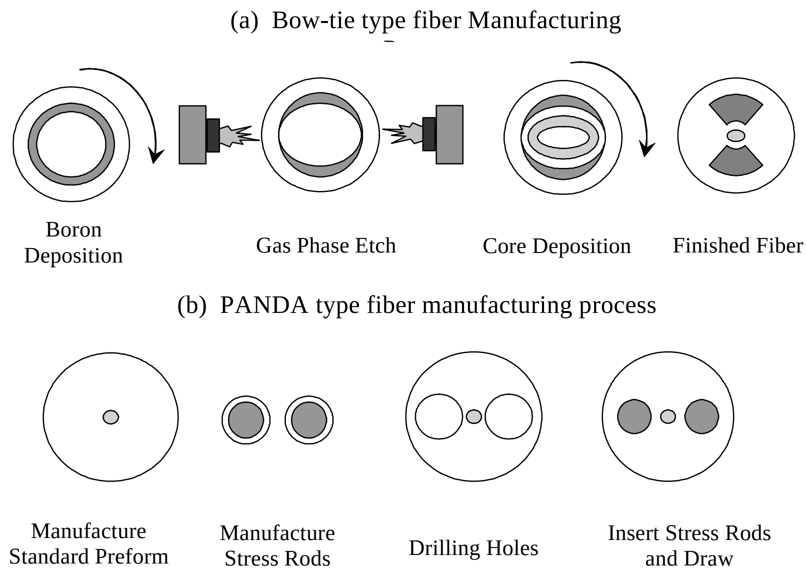


Fig. 4. Schematic diagrams illustrating the steps involved in the fabrication of (a) bow-tie and (b) Panda type PM fibers.

Fig. 4(b) shows a schematic diagram of the steps involved in making a Panda type PM fiber. As for the bow-tie fiber solution doping can be used to deposit lanthanide-doped core inside a high quality synthetic quartz tube and the tube is subsequently collapsed into a rod. However in this case the circular stress elements of desired composition are fabricated via MCVD and inserted into axial holes drilled into the finished lanthanide-doped perform prior to drawing. Panda therefore has the unique advantage of decoupling the manufacture and incorporation of the stress elements from the manufacture of the optically active core region of the preform. In addition to aiding with the manufacturability of the fiber it also has significant advantages with respect to manufacturing large volume, highly uniform fibers.

4.2. Panda PM fiber design

PM fibers rely on residual stress anisotropy across the core which arises from differences in thermal expansion coefficient between the stress members and core and cladding. The composition, location and geometry of the stress members determine the birefringence in the fiber. In PM-DCF's the core and cladding geometries are very different to standard telecommunications type PM fibers, more specifically in LMA DCF's the large diameter of the core negatively impacts the achievable birefringence. If LMA PM-DCF's were to be feasible, considerable research had to be performed in order to optimize the compositional and the geometrical design of the stress members. In 2003 the results of such detailed experimental and theoretical analyses were reported [10, 29].

Fig. 5 shows the key dimensional parameters that determine the birefringence that can be obtained in a PM-DCF. These include the size of the stress member (d_s) and the position of the stress member (d_p) relative to the inner cladding diameter (d_f) and the core diameter (d_c). In addition to the geometric factors the composition of the stress rod determines the birefringence that is achieved in the fiber. Fig. 6 shows the effect of stress rod size and location on the birefringence (and beat length) of the fiber. As can be seen from Figure 6(a) the birefringence can be increased (or the beat length reduced) by increasing the size of the stress members (d_s) and keeping all other parameters constant. Similarly, Figure 6(b) shows that the birefringence can be increased by moving the stress rods closer to the core.

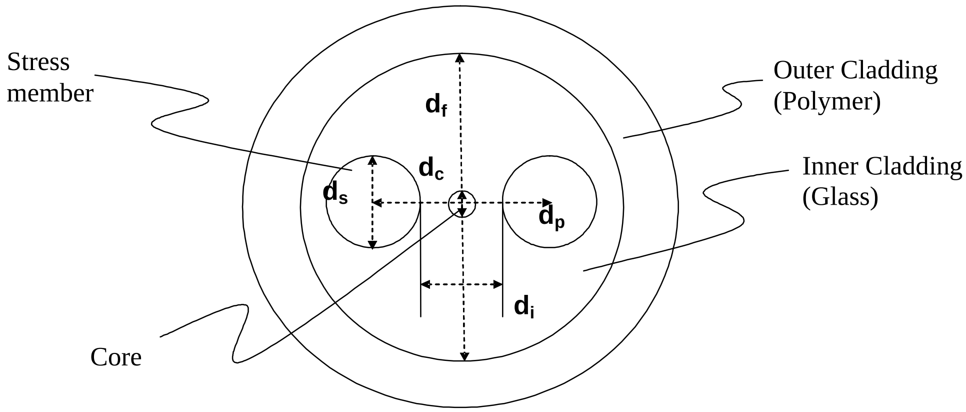
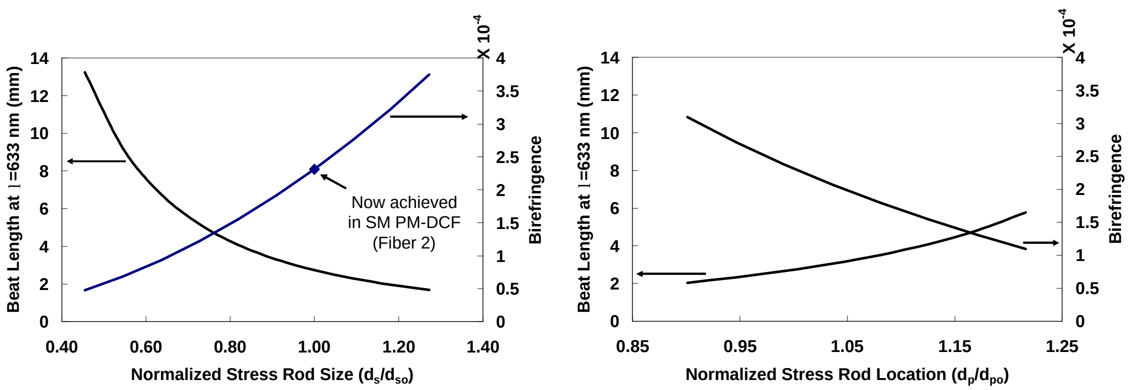


Fig. 5. Geometric considerations in a PM-DCF [10].

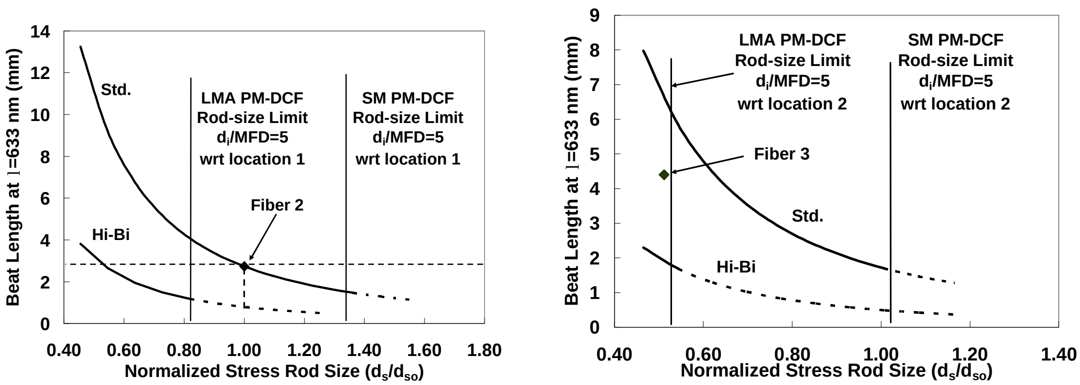


(a) (b)

Fig. 6. Birefringence and beat-length of PM-DCF's as a function of (a) stress rod size and (b) location [10].

While it is theoretically possible to use these two geometric parameters to achieve very large values of birefringence, a limiting criterion imposed on d_s and d_p is the distance of the stress members from the core. This limiting distance is indicated by distance between the inside edges of the stress members (d_i). If d_i becomes very small, the probability of overlap between the mode field and the stress members increases, resulting in increased attenuation and bend loss of the laser or amplifier signal wavelength. In order to provide a safety margin for avoiding any overlap between the modal power profile in the fiber and the stress members, we define a limiting ratio d_i/MFD> 5. For small core single mode fibers used in low to medium power applications, it is possible to achieve sufficient birefringence using standard stress member compositions and operate well within the limiting ratio. However, for large core fibers needed for high power applications, achieving sufficient birefringence while operating within the limiting ratio is more challenging.

Figures 7(a) and 7(b) show the predicted beat length as a function of the stress member size. In addition, a vertical line representing the limiting ratio d_i /MFD= 5 for SM PM-DCF is also shown. For stress rod sizes falling to the right of this vertical line are not permitted because the limiting distance, d_i, becomes small and the ratio d_i /MFD < 5. Figure 7(a) shows a second vertical line that depicts the limiting ratio for a PM-DCF with a 30 micron core. Stress member sizes to the left of the vertical line are permitted. Therefore, one can expect the stress-rods to be smaller for the PM-DCF fibers with multimode cores as compared to those with SM cores. In order to achieve a higher birefringence, it was necessary to move the stress rods closer to the center of the fiber. The predicted beat-length for the nearer location is shown in Figure 7(b). Comparing Figures 7(a) and 7(b), we can see that a higher birefringence can be attained for the same stress-rods size at location 2 compared to location 1. Fiber 3 is a large (30 μm) core PM-DCF that is suitable for high power applications. When stress-rods were placed at location 2 for this fiber, a beat length of 4.4 mm at 633 nm, corresponding to a birefringence of 1.44×10^{-4}, was obtained (Figure 7(b)). In order to stay within the limiting ratio, the stress member size had to be kept small and hence a birefringence comparable to the small core fiber was not achieved. It is clear from Figure 7 that, in the case of large core fibers, such as those used in moderate to high power lasers and amplifiers, the limit of d_i /MFD = 5 is reached well before the desired birefringence is achieved. Hence, for large core fibers, the composition of the stress member has to be changed so that higher birefringence can be achieved while using small stress members. Predicted beat lengths as a function of stress member size for another composition are also presented in Figure 7. Stress members with this composition are currently used to make PM fibers for gyroscope applications where very low beat lengths have to be achieved. A higher coefficient of thermal expansion difference, and hence higher birefringence, can be achieved with this stress member composition. It can be observed from Figure 7(b) that with this stress member composition birefringence values comparable to those of small core fibers can be achieved while using small stress members and operating within the limiting ratio.



(a) (b)

Fig. 7. Limiting birefringence using standard and high birefringence rods in SM and LMA fibers for different stress-rod locations (a) location 1 and (b) location 2 [10].

4.3. Optical characterization of Panda PM fiber

A broad range of ytterbium-doped LMA DCF's, whose characteristics are optimized for a variety of output powers, are now commercially available [30]. An optical image showing the cross section of such a fiber, with a 20micron core and 400micron inner-cladding diameter is presented in Fig. 8.

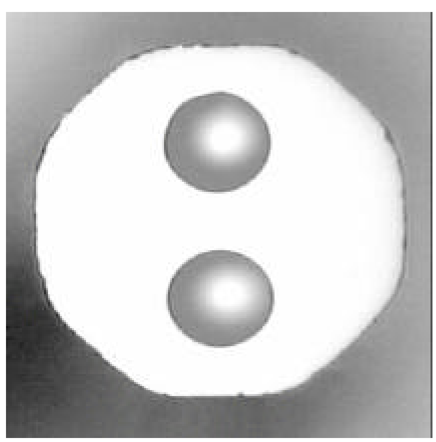


Fig. 8. Cross-section of a 20micron core, 400micron inner-clad Panda type ytterbium-doped LMA PM-DCF.

These fibers have a 0.46NA fluorinated polymer optical cladding surrounded by a more standard telecommunications type jacket (for abrasion resistance). These fibers have been demonstrated to exhibit excellent slope efficiencies. Fig. 9 shows the 76% slope efficiency of the 20micron/400micron ytterbium-doped PM-LMA DCF, in a hybrid cavity with bulk optics and PM fiber (see Ref 31 for full details). Excellent polarization extinction ratio, grater than 95% up to the maximum output power of 300W was obtained with diffraction limited beam quality. The fiber was pumped using wavelength multiplexed diodes at 940nm and 975nm, and the fiber length around 45m. Output power was limited only by the available pump power and in fact it is anticipated that the maximum cw output power for this fiber design will be very close to 1kW. Indeed this fiber and it's 30micron/400micron sister fiber are currently being evaluated by a number of laser and amplifier research groups from whom it is anticipated that world record diffraction-limited output powers will reported over the coming months. Such reports will include diffraction-limited output powers in excess of 700W from the LMA-YDF-20/400 and as with previous results this output is pump-limited [32].

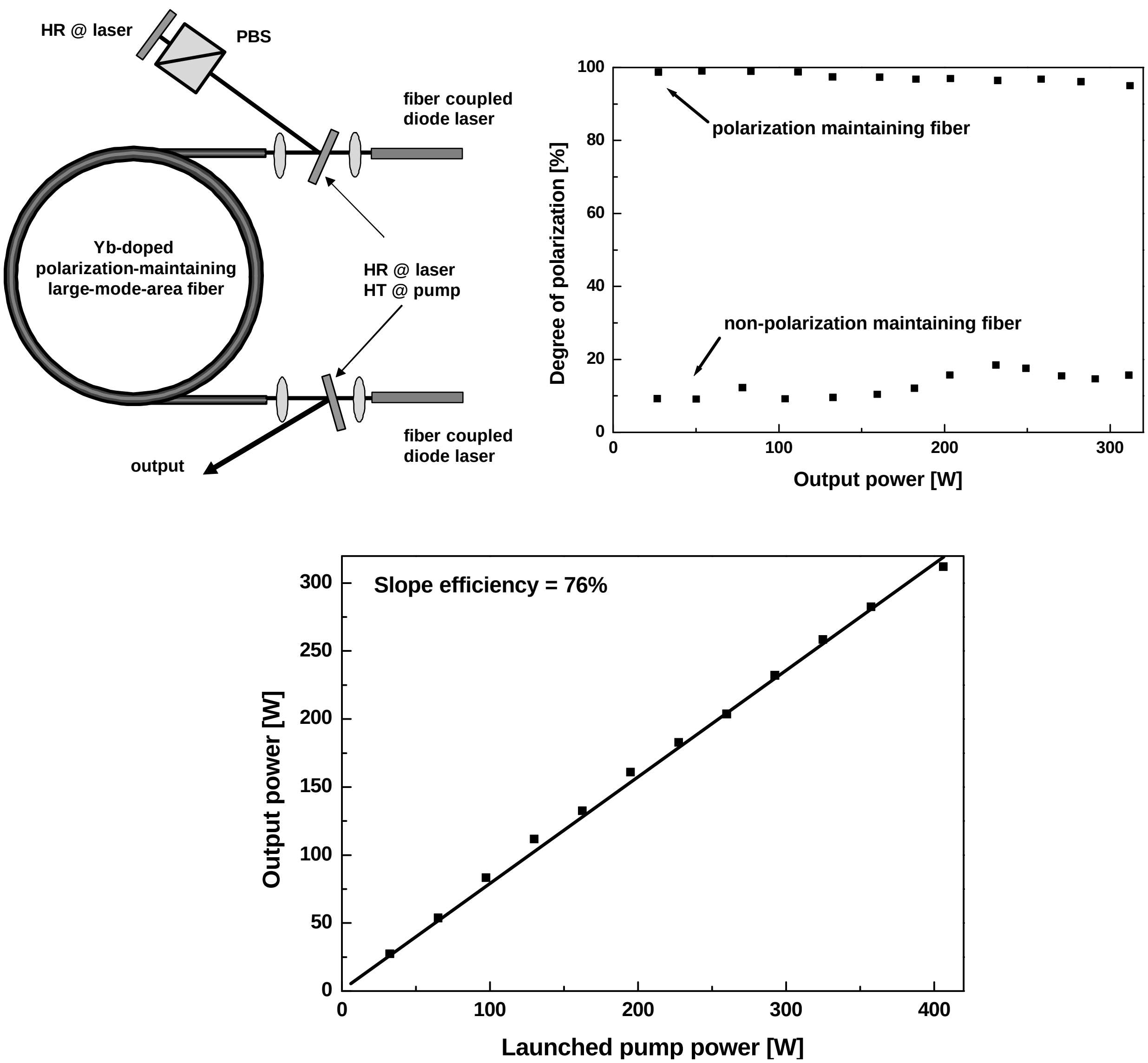


Fig. 9. Slope efficiency and PER for the linear polarized fiber laser cavity shown, and based on 20/400 PM-LMA [Ref 31].

5. CLADDING DESIGN AND GEOMETRY

The size of the inner cladding of DCF's is typically determined by the brightness of the pump sources, with larger clad diameters aiding the injection of higher pump powers. At the same time for a given core diameter the cladding absorption reduces with the square of the increase in cladding diameter and so longer lengths are required and the threshold for nonlinear processes is reduced. Consequently the cladding diameter must be chosen in combination with the desired output level and the size and dopant concentration of the core. Furthermore for lanthanide ions whose lasing transitions are three-level in nature, such at ytterbium and erbium, the use of shorter fiber lengths aids in the shifting of lasing wavelengths towards the blue end of the spectrum through the bleaching of reabsorption loss. In fact Selva *et al* [33] recently reported an ytterbium-doped DCF with a lasing wavelength of 977nm using a high NA (>0.7) air-clad geometry. Such devices are attractive for using as pump sources for erbium-doped fibers or frequency doubling into the blue. In most situations, lasing at such low wavelengths is difficult because the overlap of the pump field with the gain region is small, consequently relatively long fiber lengths are required and overcoming the reabsorption at low wavelengths is difficult. By reducing the inner cladding area the threshold was reduced which in turn necessitated the use of a high cladding NA to facilitate efficient coupling of the pump source.

Ultimately, the amount of pump power that can be coupled into an optical fiber is determined by the size and the NA of the cladding. Moreover it scales with the square of the NA and so the role of the outer cladding is to provide a high NA, low loss, mechanically durable jacket with a high threshold to optical damage (from the pump). Furthermore the use of higher NA claddings facilitates the less expensive pump sources. Most commercially available products currently employ the use of a fluorinated polymer and whilst some of these have shown to be surprisingly durable (Nufern's standard 0.46NA coating material has yet to demonstrate an optically induced failure) an all-glass solution is actively being sought due to its perceived superior damage performance. Whilst glass has a higher maximum operating temperature, damage threshold and thermal conductivity than polymer materials, most DCF's employ silicate host glasses and the achievable NA of a solid all-glass host is severely limited by the ability to incorporate large quantities of fluorine and/or boron. Indeed commercially available glasses typically have a maximum NA of around 0.26. Consequently some attention has been turned to developing air-clad fibers wherein the inner cladding is surrounded with a web of silica bridges which are substantially narrower than the wavelength of the guided radiation [34, 35]. NA's of up to 0.8 have been reported [36] and images of fiber structures with 0.55NA and 0.66NA are shown in Fig. 10.

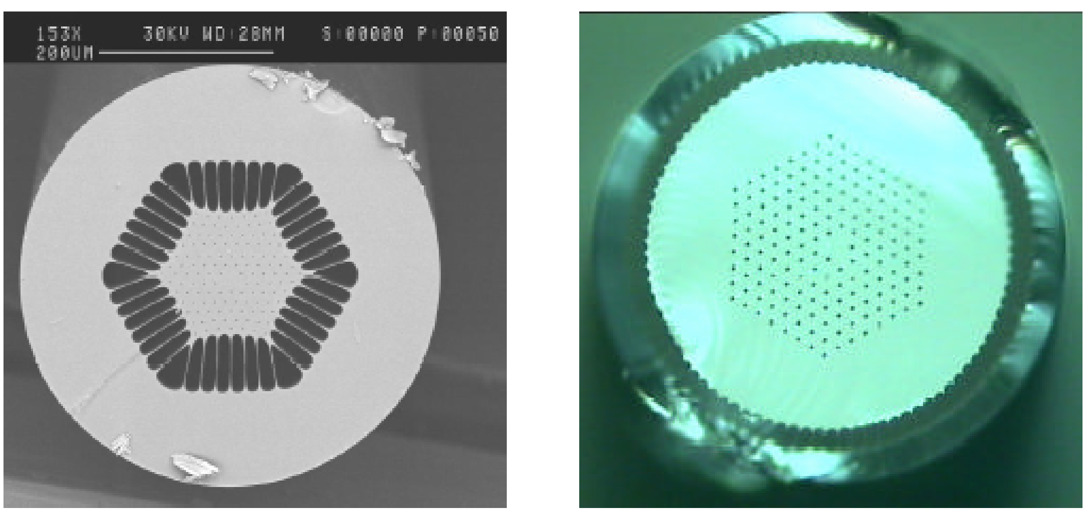


Fig. 10. SEM image of 0.55NA (left) and optical image of a 0.66NA (right) air-clad ytterbium-doped LMA fibers [37].

Such fibers are clearly suitable for high power applications but questions remain as to their suitability for volume production and long-term mechanical reliability.

6. CONCLUSIONS

With extremely high wallplug efficiencies and high output beam qualities from compact, rugged, reliable, passively cooled devices the ytterbium-doped fiber laser has attracted significant attention in recent times. Over the last eighteen months a series of advances in fiber and pump-diode design have facilitated an exponential increase in the reported output powers of cw and pulsed fiber sources. So much so that it would seem that diffraction-limited, single-polarisation, kW output powers from a single fiber laser will soon become a reality. As a consequence fiber lasers based upon these designs are now challenging more traditional bulk solid-state and gas laser systems in a range of both industrial and military, sensing and material processing applications.

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