Continued advancements in the designs of double clad fibers for use in high output power fiber lasers and amplifiers

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ABSTRACT

Fiber lasers have a number of distinct advantages over their more conventional solid state laser alternatives. These advantages include size, reliability, wavelength selectivity, heat dissipation, wall plug efficiency and operational cost. Furthermore they can be operated without the need for active cooling or optical alignment. Consequently the market for these more traditional laser sources are beginning to be eroded by the emergence of fiber lasers.

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 [1]. 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 [2]. 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 output powers, now approaching the kW-level from a single fiber [3, 4, 5].

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 coherently combine the beams from multiple fibers and this it turns 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 [6]. In this paper we review the recent and ongoing advances in fiber design that is facilitating the development and production of lasers and amplifiers with ever increasing output powers.

Keywords: Double clad fibers (DCF), Large mode area (LMA) fiber, Polarization Maintaining (PM), Fiber laser.

1. INTRODUCTION

The lanthanide-doped glass fiber laser was invented in the 1960's [7, 8, 9] 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 [10] this limitation was removed and in 1999 the world's first single-mode fiber laser exhibiting in excess of 100W cw output was demonstrated [1]. 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.

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.

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

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 and furthermore 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 [13, 14]; using special cavity configurations [15]; tapering the fiber ends [16] ; adjusting the seed launch conditions [17] ; and coiling the fiber to induce substantial bend loss for all transverse modes other than the fundamental [18]. 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.

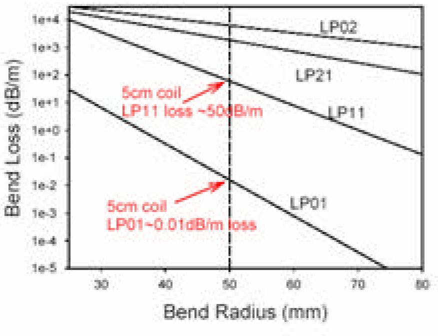


Fig. 1. Bend loss as a function of bend radius for a 0.06NA, 30micron core diameter fiber.

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.

3. POLARIZATION MAINTAINING LMA DOUBLE CLAD FIBER (PM-LMA-DCF)

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-DCFs, through optimization 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 [19, 20]. 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 [21] and more recently in a single fiber with poor beam quality [4]. 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 [22, 23]. 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 PM-DCFs in recent years.

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. Consequently, whilst passive polarization maintaining fibers have been commercially available for many years, actively doped PM fibers have not been available until recently [24, 25]. In fact an amplifier employing Yb-doped PM-DCF was first reported by Kliner *et al* [25] in 2000. If PM-LMA-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 [6, 26].

Fig. 2 shows the key dimensional parameters that determine the birefringence that can be obtained in a PM-DCF.

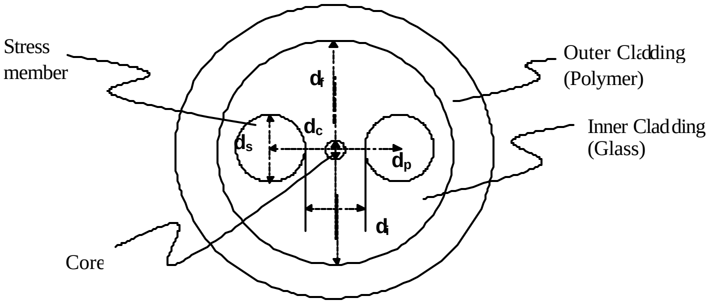
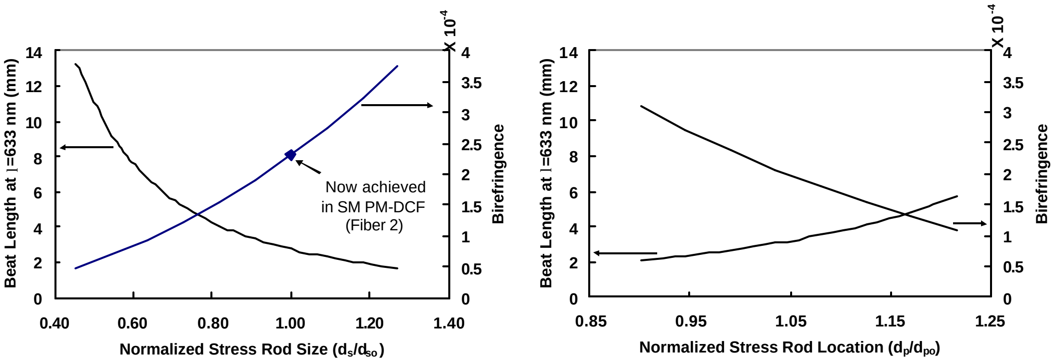


Fig. 2. Geometric considerations in a PM-DCF [6].

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. 3 shows the effect of stress rod size and location on the birefringence (and beat length) of the fiber. As can be seen from Fig. 3(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, Fig. 3(b) shows that the birefringence can be increased by moving the stress rods closer to the core.



(a) (b)

Fig. 3. Birefringence and beat-length of PM-DCF's as a function of (a) stress rod size and (b) location [6].

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. In such cases a higher coefficient of thermal expansion difference, and hence higher birefringence, can be achieved by adjusting the composition of stress members such that they are similar to those used for gyroscope fibers. Indeed a broad range of ytterbium-doped LMA DCF's, whose characteristics are optimized for a variety of output powers, are now commercially available [27]. An optical image showing the cross section of such a fiber, with a 20micron core and 400micron inner-cladding diameter is presented in Fig. 4.

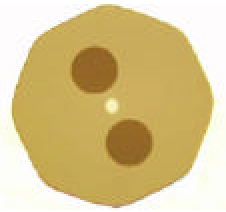


Fig. 4. Cross-section of a 20micron core, 400micron inner-clad Panda-type ytterbium-doped PM-LMA-DCF.

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. 5 shows the 76% slope efficiency of the 20micron/400micron ytterbium-doped PM-LMA DCF, in a hybrid cavity with bulk optics and PM fiber [28]. Excellent polarization extinction ratio, greater 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 was around 45m. Importantly, the 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 diffraction-limited output powers in excess of 800W from the non-PM version of this fiber (LMA-YDF-20/400) have already been reported [29].

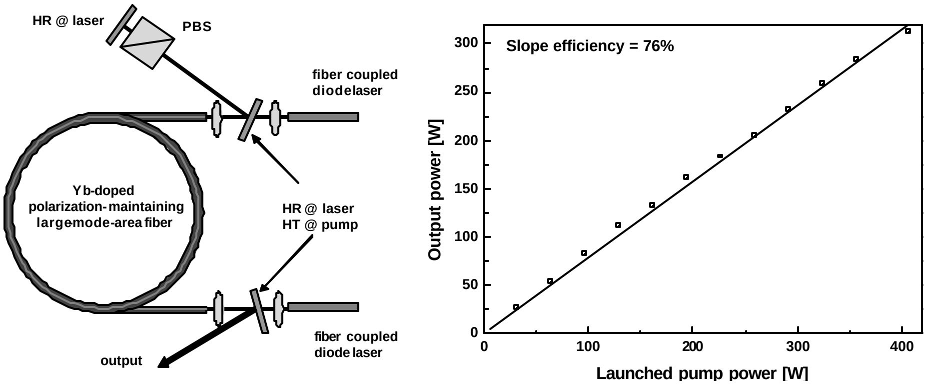


Fig. 5. Slope efficiency for the linear polarized fiber laser cavity shown, and based on 20/400 PM-LMA [28].

Typically however these high power results have been achieved in cavities employing bulk optic devices, such as polarization beam splitters. An "all-fiber" device would be more compact, robust and reliable and would probably also exhibit superior optical performance (ie. less susceptible to misalignment). Such a cavity requires tapered fiber bundles, Bragg gratings and splicing technology and indeed all these devices are currently being developed. Moreover we have recently demonstrated we have demonstrated a monolithic linearly-polarized (extinction 19dB) fiber laser producing high power (306W) diffraction-limited beam (M^2~1.1) with a stabilized, narrow-linewidth (0.57nm) spectrum at 1086nm. This simple cavity employed a 33m length of PM-LMA-YDF-20/400 spliced to a >99% FBG (Fig. 6). The cavity was coiled to 9cm diameter to eliminate the undesired polarisation-mode and higher-order transverse modes. It was pumped with a total of 496W at 915nm, 940nm and 976nm and demonstrated a threshold of around 3W and a slope efficiency of 62%. Our analysis indicates that output power using this design is scalable to 1kW cw and higher. This simple and robust all-fiber design is particularly attractive for further fiber-laser power scaling to >10kW using multiple-beam combining techniques, and is promising to facilitate a broad variety of practical applications requiring high-power linearly-polarized diffraction-limited laser beams.

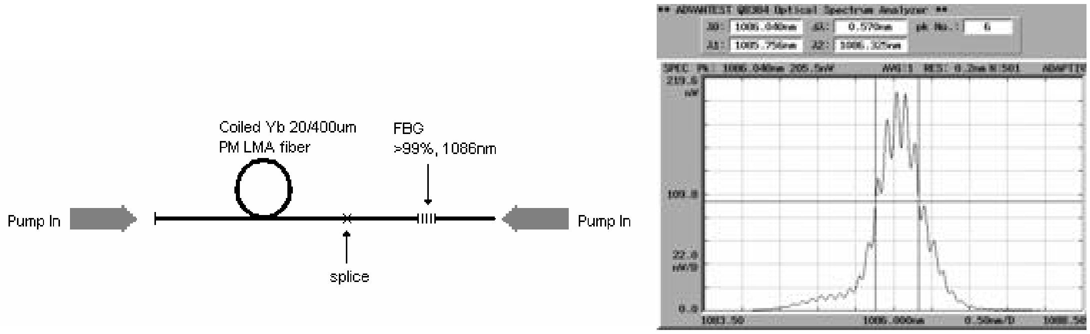


Fig. 6. Output spectrum for the all-fiber based linearly polarized single-mode fiber laser cavity.

4. 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-polarization, 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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