PM double-clad fibers for high power lasers and amplifiers

Kanishka Tankala, Adrian Carter, David Machewirth, Julia Farroni,
Jaroslaw Abramczyk and Upendra Manyam
Nufern, 7 Airport Park Road, East Granby, CT 06026
Phone: (860) 408 5000; FAX: (860) 408 5080

ABSTRACT

Fibers for high-power laser and amplifier applications require large claddings with high numerical apertures for efficiently coupling pump energy. In addition, such fibers should have high rare-earth dopant concentrations in relatively large cores, with low numerical apertures, to reduce non-linearities. Furthermore, polarization maintaining double-clad fibers (PM-DCF) are needed for coherently combining the outputs of several lasers/amplifiers to achieve output powers in excess of 100 kW for military and industrial laser applications. In this paper, we report the progress made towards fabricating PM double-clad fibers, with a variety of fiber characteristics, to facilitate development and production of high-power lasers and amplifiers. In particular, a Panda-type PM-DCF with a 0.06 NA, 30 micron diameter, Yb-doped core is reported. We also discuss various criteria that are critical for designing these PM double clad fibers.

Keywords: Yb-doped fibers, Polarization maintaining, PM Double-clad fibers, Large mode area fiber, laser fiber, amplifier fiber

1 INTRODUCTION

Yb doped fibers offer high output powers and excellent conversion efficiencies over a broad range of wavelengths (~975 to ~1200 nm)[1]. In addition, unlike erbium doped amplifiers, complications such as excited state absorption and concentration quenching are avoided in Yb doped fiber lasers and amplifiers. As a result, a high concentration of Yb ions can be incorporated while maintaining good conversion efficiencies. These attributes of Yb doped fibers, along with the advent of double-clad fiber (DCF) technology[2], have resulted in substantial interest in high-power lasers and amplifiers for various applications. Yb-doped double-clad fibers are finding current and potential applications in military and aerospace, materials processing, printing and marking, spectroscopy, telecommunications, etc[1-4].

For many high-power laser and amplifier applications, operation under stable linear polarization is becoming a requirement.[3,4] High-power amplifier (or laser) architectures are based on coherently combining the output of several DC fiber amplifiers. With the growing need for output powers of >100 kW (CW) for military and aerospace application and several kW outputs for industrial applications, there has been an increasing demand for polarization-maintaining double clad fibers (PM-DCF). In the past, different approaches have been suggested to obtain PM operation using non-PM fibers[4,5]. However, these approaches have their limitations and the preferred technology is to use a PM-DCF. While passive polarization maintaining fibers have been commercially available for several years, active PM fibers[6,7] have not been available until recently. Kliner *et al*[7] were the first to report a polarization maintaining, Yb-doped, double-clad fiber amplifier employing a bow-tie fiber. Although a bow-tie type PM-DCF is acceptable for proof of concept and research and development, it has substantial limitations in terms of preform manufacturability, uniformity and scalability.

Single mode, Yb-doped, double-clad fibers lend themselves well to applications requiring compact lasers with diffraction-limited output. However, the scalability of output powers can be limited by amplified spontaneous emission and nonlinear processes such as stimulated Raman scattering (SRS) and stimulated Brillouin scattering (SBS). These limitations can be overcome by using low numerical aperture (NA) single mode fibers with large mode areas (LMA). The low NA of the core limits the capture of the spontaneous emission by the core while the large mode area increases the threshold for SRS and SBS. In a second approach, researchers have used MM rare earth doped fibers and suppressed higher-order modes by deploying the fiber in a specific coiled configuration[8], optimizing launch conditions of the seed beam[9,10], designing fibers with specific refractive index and dopant profiles[11], and using specific cavity configurations[12]. The use of a MM fiber in single mode operation provides similar advantages as the LMA fibers.

It is apparent from the foregoing that there is a need for polarization maintaining, low NA, large core fibers for use in high power lasers and amplifiers capable of delivering as high as 100 kW output powers in continuous wave operation. In addition, since the amplifier architectures involve coherently combining output of tens, if not hundreds, of fiber amplifiers, it is essential that the technology chosen for preform and fiber fabrication is scalable for volume production and capable of producing very uniform fibers. This paper describes the technology choices we have made to facilitate development and production of high power sources using PM-DC fibers. Furthermore, the design considerations and progress made towards developing large core, low NA, Yb-doped, Panda type, PM-DC fibers are presented. We report a Panda type PM-DCF with a 0.06 NA, 30 micron Yb-doped core and a 400 micron diameter inner cladding with a numerical aperture of 0.37.

2 DESIGN, FABRICATION AND CHARACTERIZATION

2.1 Bow-tie type PM-DCF

The bow-tie type PM Yb-doped double clad fiber fabricated by modified chemical vapor deposition (MCVD) was evaluated as part of the research for this paper. Figure 1(a) shows a schematic diagram of the steps involved in making a bow-tie type PM fiber. A high quality synthetic quartz tube was used as a substrate and several layers of borosilicate glass were first deposited on the inner wall of a rotating substrate tube. Next the substrate rotation is stopped and using a specialized ribbon burner the boron in the glass is volatilized from a selected sector of the deposited layer. 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 boron has been volatilized are diametrically opposite to each other and dimensionally equal. Several layers of glass are further deposited before the Yb-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 to any significant extent. The Yb-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. The collapsed preform is further processed to obtain the desired inner cladding and drawn with a low-index fluoroacrylate coating to provide the second cladding to guide the pump light. Using this methodology a bow-tie type Yb-doped PM-DCF was fabricated.

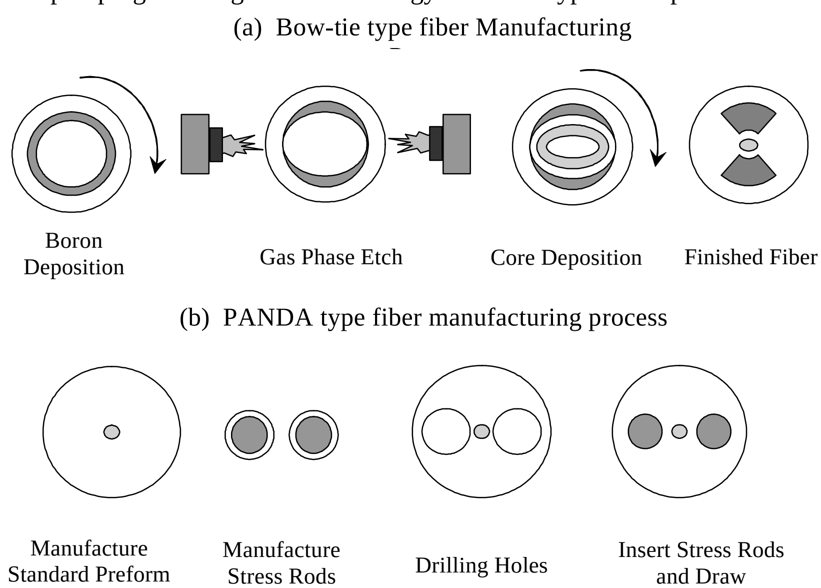


Figure 1 – Schematic diagrams illustrating the steps involved in the fabrication of (a) bow-tie and (b) Panda-type polarization maintaining fibers.

2.2 Panda-type PM-DCF

Fabrication of this type of PM-DCF is done in two stages. Here the fabrication of the stress members is decoupled from the fabrication of the rare-earth doped preform. This provides significant advantages, to be discussed later. The rare-earth doped preform is fabricated using a proprietary solution-doping technology to yield highly uniform rare-earth and co-dopant distribution. Figure 1(b) schematically illustrates the main steps in fabricating a Panda type PM fiber. A high quality synthetic quartz tube is used to deposit the rare earth doped glass. The tube is then collapsed into a rod and further processed such that when drawn the fiber will have the desired core and inner cladding dimensions. In a separate step circular stress elements of desired composition are fabricated via MCVD. Two holes of the desired dimension are drilled, diametrically opposite to each other and on either side of the core, in the rare-earth doped preform. Two circular stress members are inserted into the holes and incorporated into the preform. The preform with the stress members is then drawn to desired size with a low index fluoroacrylate. Two Panda type PM-DC fibers were fabricated. The first fiber has a 10 μm diameter Yb-doped core with a 0.08 NA. The inner cladding is 400 μm in diameter and has a 0.45 NA.

The second fiber has a 30 μm diameter core and has NA of 0.06. The inner cladding is 400 μm in diameter and has an NA of 0.37.

2.3 PM fiber design

PM fibers rely on residual stress anisotropy across the core which arises from differences in thermal expansion coefficient (Δα) between the stress members and core and cladding. The composition, location and geometry of the stress members determine the birefringence in the fiber. The compositional design of stress members and the geometrical design of the PM-DC fiber are established using an internally developed model. A multi-stepped linked model predicts the index of refraction and the expansion coefficient of the glass based on composition of the deposited glass. This in turn is used as inputs for predicting the birefringence, based on geometric considerations. The models are routinely used in the design and development of passive 125 μm and 80 μm diameter PM fiber products for telecommunication and gyroscope applications.

2.4 Characterization

Optical characterization of the PM Yb-doped DC fibers included measurements of crosstalk, beat length, absorption, fluorescence lifetime and slope efficiency. The polarization crosstalk measurement was performed in accordance with TIA/EIA-455-193 (FOTP-193) entitled “Polarization Crosstalk Method for Polarization-Maintaining Optical Fiber and Components”. A system comprising of high-quality crystal polarizers, low birefringence optics and a computer-controlled precision alignment-system provided repeatable crosstalk measurements below -45 dB. Measurements were made on 10-meter long fiber samples, looped into 10-inch diameter coils. The secondary coating was removed from a large portion of each sample and the exposed fiber section was immersed in high refractive-index oil to strip out cladding light and ensure light propagation solely in the core.

Fiber beat length was measured using a GN Nettest S18 Dispersion Measurement System, which uses a wavelength-scanning technique known as the fixed analyzer method. Fully polarized light launched into a fiber is passed through a polarizer (the analyzer) that is fixed at the exit end. The output power is then recorded as a function of wavelength. A reference scan is then taken, without the analyzer, so that power fluctuations, due to non-PMD related effects, are taken into account. In fibers with weak mode-coupling, such as PM single mode (SM) fibers, the scan of effective power with wavelength will have a periodic intensity variation with a series of maxima and minima, as seen in Figure 2. Beat length can then be calculated for each wavelength from the spacing between the intensity peaks, using the following formula:

$$L_b = L * \frac{\Delta l}{l}$$

where $\boldsymbol{L_b}$ is the beat length, $\boldsymbol{L}$ is the length of fiber measured, l is the wavelength and Dl is the peak spacing.

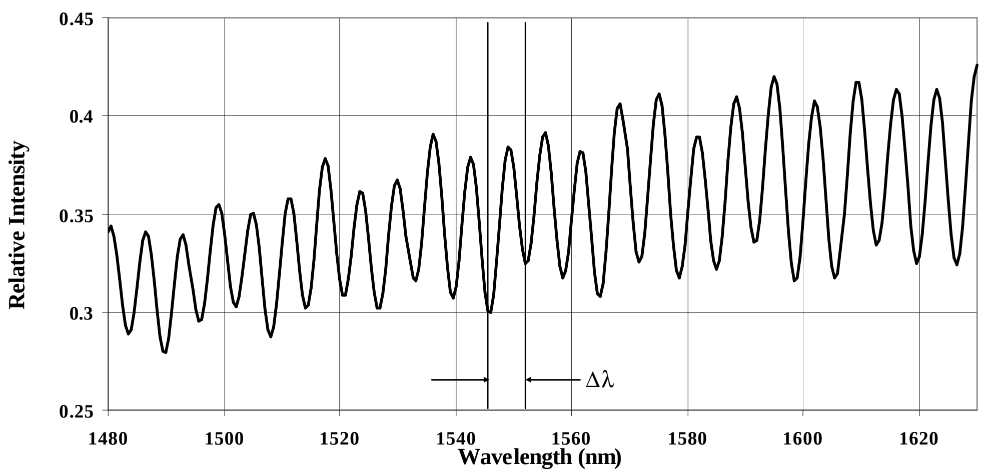


Figure 2 – PMD measurement to obtain Δλ and calculate beat length

Optical absorption for each PM-Yb-doped DC fiber was measured near 915 nm using an SDL-6380-L2 laser diode (JDS Uniphase), driven by an ILX Lightwave Model 39800 current source, and an Agilent Model 8163A lightwave multimeter with InGaAs optical head. An integrating sphere was used with the optical head to make power measurements NA insensitive, and a 915 nm band pass filter (Spectrogon) was used to block out any fluorescence resulting from the 915 nm input signal. The standard cutback method was utilized to determine fiber absorption.

Fluorescence lifetimes were measured on fiber samples using the aforementioned laser diode as a pump source. A small section of the fiber, following removal of the low-index coating, was placed next to an InGaAs detector and 1110 nm band pass filter (Spectrogon, 70 nm FWHM) so that fluorescence could be detected at a radial location from the fiber. The combination of the detector, band pass filter and a Fluke SW90W Oscilloscope was used to measure the fluorescence decay. Lifetimes are given as three e-folding times (e1 e2, e3) which describe the decay characteristics. Log-normal plots of the decay were fitted to better estimate those components of the lifetime (e2, e3) where the signal was noisy.

Slope efficiency measurements were made using the same 915 nm laser diode as a pump source. Light from the pump laser was collimated and focused using microscope objectives, appropriately chosen to best match the numerical apertures of the laser delivery fiber and Yb-DC fiber. A laser mirror, having > 99.8% reflectivity at the lasing wavelength and > 95% transmission at the pump wavelength, was placed in front of the focusing objective. A band pass filter was used, with an optical head/integrating sphere combination, to remove any pump light from the laser-power readings. A measurement schematic is shown in Figure 3.

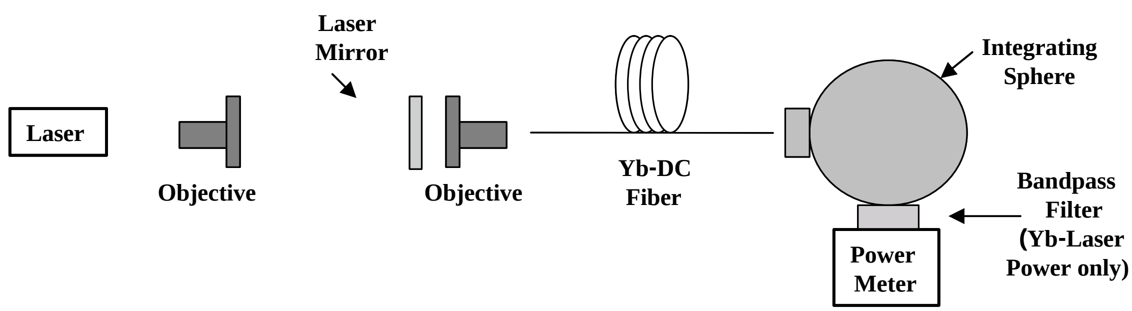


Figure 3 – Schematic of slope efficiency measurement set-up

3 RESULTS AND DISCUSSION

3.1 Fabrication of Bow-tie Vs. Panda type fibers

Two substantially different PM fiber manufacturing technologies were investigated to understand the advantages and disadvantages of the two technologies for making PM-DC fibers. The evaluation was based on two main criteria: (a) the suitability of the particular process-technology for making double-clad fibers and (b) the potential of preform scalability, reproducibility and consistency for volume production.

The bow-tie technology offers the advantage of fabricating the stress members and the rare-earth doped core in one process step. Secondly, the distance of the stress members from the core can be precisely controlled by the number of buffer layers deposited between the stress layers and the core. The stress elements can be brought very close to the core and hence, for a given size and composition of the stress element, a higher birefringence can be achieved. However, this technology has several significant disadvantages. The need to deposit stress elements and a rare-earth doped core within the same substrate tube limits the ability to independently control the polarization and lasing properties of the fiber. Second, although the stress elements can be brought close to the core, the size of the stress elements that can be deposited is restricted and limits the size of the preform that can be made with a desired birefringence. In other words, the technology doesn't lend itself to volume production. Finally, most DC fibers require a non-circular geometry of the inner-cladding which calls for some processing step, such as grinding or thermal processing, to obtain a desired geometry. In the case of a bow-tie type preform, the grinding (or thermal processing) operation has to be conducted with the stress members in place. PM performs are fairly fragile because of the large amount of stress incorporated in the preform and prone to fracture on exposure to mechanical (or thermal) shock during a grinding (thermal processing) operation. The bow-tie preform technology is therefore not preferred for making volume production of PM-DCF.

The technology used to make the Panda type of PM-DC fibers not only offers several advantages but addresses the limitations of the bow-tie technology. In this process, both the rare-earth doped preform and stress member fabrication steps are effectively decoupled, providing independent and highly effective control of the polarization properties and composition of the rare-earth doped glass. Second, fairly large stress-inducing members can be fabricated, which substantially increases the limit of preform size and makes the process more suitable for preform scale-up. Finally, all required processing to achieve a non-circular geometry can be accomplished prior to incorporating the stress-members, and hence, improve production yields. The Panda type PM technology is therefore amiable for fabricating PM-DCF and is the technology of choice for volume production.

The dimensions and polarization properties (beat length and cross talk) of various PM-DCF made using either a bow-tie design or -stress-member design are presented in Table I. Fiber 1 is a bow-tie type Yb-doped PM-DCF. Since the size of the stress regions that can be deposited was limited, only a fiber with a 200 µm inner-cladding diameter was fabricated to get the maximum possible birefringence. Fiber 2 is a -stress-member type Yb-doped PM-DCF. The relative ease of making larger stress members allowed for a fiber with a 400-µm diameter inner cladding. The beat length of the two fibers was measured using the aforementioned wavelength scanning method and the birefringence calculated. It can be noted from Table I that Fiber 1, whose dimension was minimized to maximize the birefringence, had a beat length of only 4 mm at 633 nm. In comparison, Fiber 2 gave a beat length of 2.7 mm at 633 nm, even with an inner-cladding diameter of 400 µm. The results demonstrate that it is relatively easy to achieve higher birefringence in Panda type PM-DC fibers compared to bow-tie type PM-DCfibers.

3.2 Optical properties of Yb-doped PM-DCFs

As discussed in the introductory section of this paper high power laser and amplifier applications require fibers with low numerical apertures and large cores to obtain high pulse energies and increase the threshold for non-linear effects. In addition, polarization maintaining versions are needed to coherently combine the outputs of several fibers to achieve 10s to 100s of kW of output power. Kliner *et al*[7] demonstrated a polarization maintaining amplifier using a bow-tie type PM-DCF (made similar to Fiber 1) with a low NA core. However, the core was only 10 µm in diameter. Recent work has shown that multimode rare earth doped fibers can be used in several configurations[8-12] to achieve single mode operation. This technology is expected to enable the construction fiber lasers capable of delivering > 100 kW output. However, polarization maintaining versions of double-clad fibers with multimode, low NA, rare earth doped cores are needed to realize this goal.

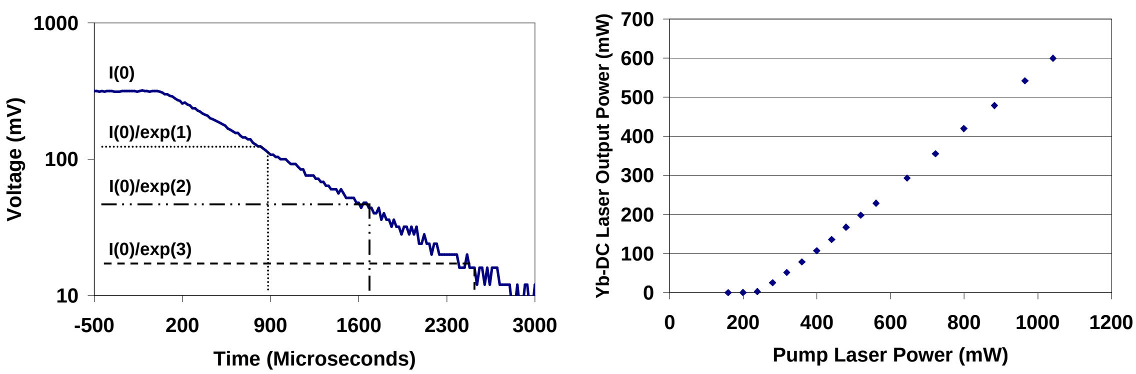
Table I. Characteristics of bow-tie and Panda-type PM fibers

	Fiber 1	**Fiber 2**	**Fiber 3**
Stress Member Type	Bow-tie	Panda	Panda
Core Size (µm)	10	10	30
Core NA	0.06	0.08	0.06
Clad Size (µm)	180	400	400
Clad NA	0.31	0.45	0.37
Absorption at 915/975 nm (dB/m)	0.65 / 2.14	0.26 / 0.86	0.67 / 2.2
Lifetimes e1, e2, e3 (microseconds)	870, 850, 870	850, 810, 840	880, 820, 840
Crosstalk (dB) 10 meters, 10 inch coil	-26	-41.5	-30
Beat Length normalized to 633 nm (mm)	4	2.7	4.4
Birefringence ($x10^{-4}$)	1.58	2.34	1.44

Two Panda type and one bow-tie type PM-DCF were fabricated. All fibers had low NA cores in the range of 0.06 to 0.08. The specific parameters such as core size, NA, clad size, absorption, etc for these fibers are presented in Table I. The cores of all fibers were doped with ytterbium and suitable co-dopant(s) to promote homogeneous dispersion of the Yb-ions. However, these co-dopants often raise the refractive index of the core and can only be used in limited amounts to achieve a low core NA. It is therefore essential to ensure that sufficient co-dopants are available to prevent quenching of the fluorescence.

Fluorescence lifetimes were measured on all fibers, therefore, to get an idea of efficiency. Figure 4(a) shows the fluorescence lifetime typical of these fibers. The lifetimes for all three fibers are about 0.9 ms, similar in magnitude to other Yb^{3+}-doped silicate-glass lifetimes reported in the literature[13,14,15]. In addition, the closeness of the e2, e3 times to e1 (for all fibers) indicate the Yb-ions are decaying at the same rate, i.e. the ions appear to be homogeneously dispersed.

Three e-folding times of similar magnitude, however, may not fully indicate a low fluorescence-quenching glass. Paschotta *et.al*[14] have reported quenching of Yb^{3+} fluorescence in silicate glass fibers, under lasing conditions, with Yb^{3+} levels as low as 1200 ppm (by weight), even though no quenching behavior was exhibited from the measured fluorescence lifetime. Emission quenching was attributed to a non-radiative decay on the order of a few microseconds, at most, that could not be detected with their measurement system. They also fabricated a particular fiber sample (2300 ppm Yb^{3+} by weight) that did not exhibit fluorescence quenching, and therefore attributed the cause of non-radiative effects to be processing-induced. In a later publication, Burshtein *et.al*[15] reported similar Yb^{3+} fluorescence quenching having rates between 6-300 microseconds. Given the response time of our measurement system is 10's of microseconds, we cannot conclusively say, from the lifetime measurements alone, the Yb-DC fibers will be efficient if the non-radiative effects are on the order of 1-10 microseconds. However, no quenching rates between 100-300 microseconds could be observed.



(a) (b)

Figure 4 – (a) Fluorescence Lifetime and (b) Slope efficiency measurement from Yb-doped PM-DCF

A more conclusive indication of fiber performance is a direct measurement of slope efficiency, as seen in Figure 4(b). A measured slope efficiency of 77% was obtained, with the lasing wavelength of about 1090 nm and a threshold near 250 mW. This measured efficiency is very close to the quantum limit of 84% for these pump and signal wavelengths. The results clearly indicate a low NA fiber doped can be fabricated having high efficiency and a suitable concentration of rare-earth ions.

Using this glass composition a Panda type PM-DCF with a 0.06 NA, 30 micron diameter, Yb-doped core was fabricated. The fibers has an inner-cladding diameter of 400 µm and is coated with a low index polymer, providing inner cladding NAs of 0.37. The low index polymer coating is further protected by a standard, telecom-grade acrylate coating. The PM-DCF with a multimode core (fiber 3) exhibited an absorption of 0.67 dB/m @ 915 nm (2.2 dB/m @ 975 nm). The beat length of the fiber was measured to be 4.4 mm @ 633 nm which corresponds to a birefringence of 1.44×10^{-4}. Although a PM-DCF with a 30 micron diameter core has been demonstrated, it is expected that further work is needed to enhance the birefringence in the fiber. The following sections discuss the design considerations in making PM-DCF and the analysis indicates that birefringence can be substantially increased. Thus, PM-DC fibers with low NA, multimode cores are practical and can be expected to play a significant role in the development and production of high power lasers and amplifiers.

3.3 Polarization characteristics and design criteria

Figure 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. Figure 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.

Presented at Photonics West 2003 – San Jose, CA, Tuesday, January 28, 2003

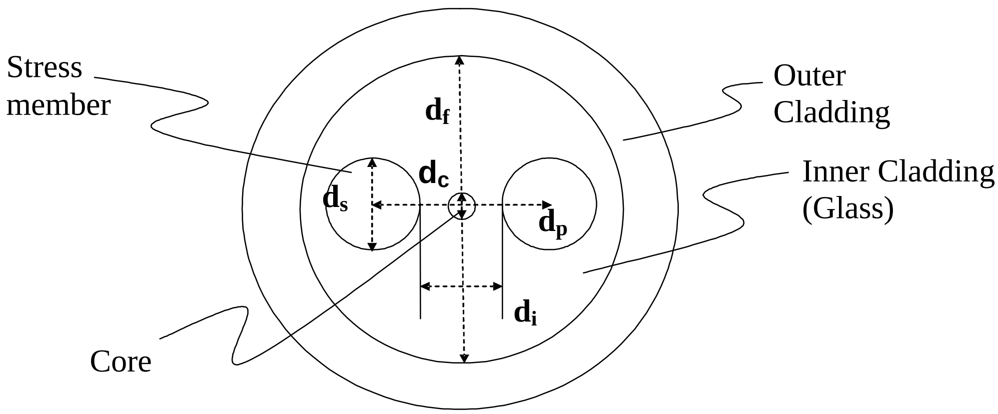


Figure 5 – Geometric considerations in a polarization maintaining double-clad fiber

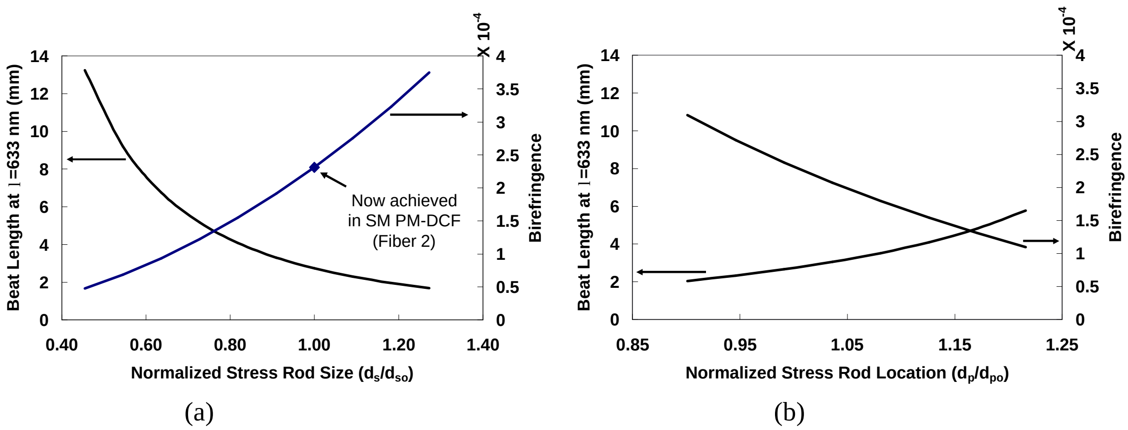
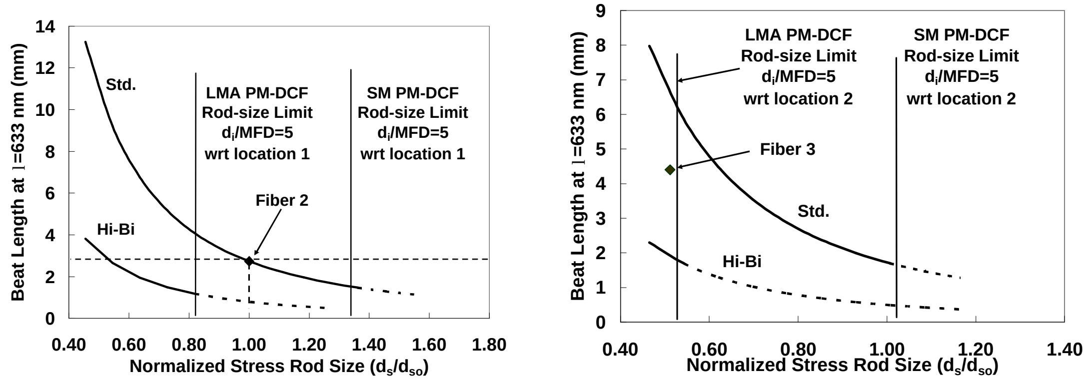


Figure 6 – Birefringence and beat-length of PM double clad fibers as a function of (a) stress rod size and (b) location

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 at 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.

Fiber 2 is an example of PM-DCF for use in low to medium power applications and has small (10 μm) core. A beat length of 2.7 mm at 633 nm, which corresponds to a birefringence of 2.31×10^{-4}, was measured for Fiber 2. Figures 7(a) and 7(b) show the predicted beat length as a function of the stress member size. The experimentally measured beat length for Fiber 2 is plotted for reference in Figure 7(a). 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. It is clear that Fiber 2 is well within the limiting ratio and a fairly low beat length has been achieved. It is also observed from Figure 7(a) that for a small core fiber a beat length of less than 2 mm can be achieved without crossing the limiting ratio.



(a) (b)

Figure 7 – Limiting birefringence using standard and high birefringence rods in SM (Fiber 1) and LMA (Fiber 2) for different stress-rod locations (a) location 1 and (b) location 2

Figure 7(a) shows a second vertical line that depicts the limiting ratio for a PM-DCF with a 30 micron core (Fiber 3). 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 beat-length 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 $1.44x10^{-4}$, 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 birefringence of 3.5×10^{-4} can be achieved in large core fibers, which is comparable to the birefringence in small core fibers with standard stress rods.

4 CONCLUSION

There is a growing need for low numerical aperture, large (multimode) core, PM-DCF for high power laser and amplifier applications. Slope efficiencies as high as 77% can be achieved in low NA (0.06) Yb-doped PM-DCFs. Evaluation of two PM fiber fabrication technologies indicated that substantial birefringence can be achieved in Panda type PM-DCFs and the Panda manufacturing process is the preferred technology over bow-tie technology for volume production of PM-DCFs. A Panda type PM-DCF with a 0.06 NA, 30 micron Yb-doped core (absorption of 0.67 dB/m and 2.2 dB/m at 915 nm and 975 nm respectively) and a 400 micron diameter inner cladding with a numerical aperture of 0.37 has been demonstrated. Experimental and modeling results indicated that certain special considerations have to be taken into account for making PM-DCFs with multimode Yb-doped cores. The analysis shows that large core PM-DCFs with sufficiently high birefringence are practical. Thus, PM-DC fibers with low NA, multimode cores are practical and can be expected to play a significant role in the development and production of high power lasers and amplifiers.

REFERENCES

1. R. Paschotta, J. Nilsson, A.C. Tropper and D.C. Hanna, "Ytterbium doped fiber amplifiers," *IEEE Journal of Quantum Electronics*, **33(7),** 1049-1056, 1997.
2. L. Zentono, "High-power double-clad fiber lasers," *Journal of Lightwave Technology*, **11(9)**, 1435-1446, 1993.
3. J. Noda, K. Okamoto and Y. Sasaki, "Polarization maintaining fibers and their applications," *Journal of Lightwave Technology*, **4(8)**, 1071-1089, 1986.
4. J. P. Koplow, L. Goldberg, R.P. Moeller and D. A. V. Kliner, "Polarization-maintaining, double-clad fiber amplifier employing externally applied stress-induced birefringence," *Optics Letters*, **25(6)**, 387-389, 2000.
5. I. N. Duling III and R. D. Esman, "Single-polarisation fibre amplifier," *Electronics Letters*, **28(12)**, 1126-1128, 1992.
6. K. Tajima, "Er^{3+}-doped single-polarisation optical fibres," *Electronics Letters*, **26(18)**, 1498-1499, 1990.
7. D. A. V. Kliner, J. P. Koplow, L. Goldberg, A. L. G. Carter and J. A. Digweed, "Polarization-maintaining amplifier employing double-clad bow-tie fiber," *Optics Letters*, **26(4)**, 184 – 186, 2001.
8. J. P. Koplow, D. A. V. Kliner and L. Goldberg, "Single-mode operation of a coiled multimode fiber amplifier," *Optics Letters*, **25(7)**, 442-444, 2000.
9. M. E. Fermann, "Single-mode excitation of multimode fibers with ultra-short pulses," *Optics Letters*, **23(1)**, 52-54, 1998.
10. O. G. Okhotnikov and J.M. Sousa, "Flared single-transverse-mode fibre amplifier," *Electronics Letters*, **35(12)**, 1011-1013, 1999.
11. H. L. Offerhaus, N. G. Broderick, D. J. Richardson, R. Sammut, J. Caplen and L. Dong, "High-energy single-transverse-mode Q-switched fiber laser based on a multimode large-mode-area erbium-doped fiber," *Optics Letters*, **23(21)**, 1683-1685, 1998.
12. U. Greibner and H. Schonnagel, "Laser operation with nearly diffraction-limited output from a Yb-YAG multimode channel waveguide," *Optics Letters*, **24(11)**, 750-752, 1999.
13. M. Digonnet, Rare-Earth Doped Fiber Lasers and Amplifiers (Second Edition), Marcel Dekker, Inc. NY, 2001, 637.
14. R. Paschotta, J. Nilsson, P.R. Barber, J.E. Caplen, A.C. Tropper, and D.C. Hanna, "Lifetime quenching in Yb-doped fibers", *Optics Communications*, **136**, 375-378, 1997.
15. Z. Burshtein, Y. Kalisky, S.Z. Levy, P. Le Boulanger and S. Rotman, "Impurity local phonon nonradiative quenching of Yb^{3+} fluorescence in Ytterbium-doped silicate glasses", *IEEE Journal of Quantum Electronics*, **36 (8)**, 1000-1007, 2000.