Large Mode Area Double Clad Fibers for Pulsed and CW Lasers and Amplifiers

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

ABSTRACT

The advent of double clad fiber technology has made high power lasers and amplifiers possible. 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 apertures (NAs), large-mode areas (LMAs), novel index profiles and high dopant concentrations. This paper discusses advances made in design and fabrication of highly efficient, large-mode area double clad fibers. Experimental and modeling results pertaining to changes in mode area, resultant power density and nonlinear threshold with changing core size are discussed. In addition, the mechanical reliability of the LMA fibers is discussed.

INTRODUCTION

Developments in manufacture, and devices incorporating, rare earth doped, large-mode area (RE-LMA) double clad fibers have increased greatly over the past few years. Advances in RE-LMA fiber fabrication, including polarization-maintaining (PM) versions, not only enabled the production of large yields of uniform product but has also allowed flexibility of fiber design[1]. Laser output powers well exceeding 100 W with diffraction-limited beam quality, from a single RE-double clad fiber, have been demonstrated, as well as multiple-millijoule amplifier peak powers[2]. Research in beam-combining techniques, such as coherent and spectral, may enable high brightness, single-mode sources >> 1 kilowatt output power[3-5]. Although not inherently single mode, RE-LMA fibers have been made to operate with near diffraction limited outputs via coiling[6] or optimized launch condition techniques[7].

The advantages of RE-LMA fibers are realized by understanding the limiting mechanisms of output power for a typical laser or amplifier. One such mechanism is amplified spontaneous emission (ASE), which extracts energy from the fiber in an incoherent manner. RE-LMA fibers have cores with low numerical apertures (NAs), typically smaller than single-mode telecom fibers. This reduction in core NA reduces the amount of fluorescence captured by the core and thus the reduction of amplification of that fluorescence. A second mechanism, non-linear in nature, is stimulated Brillouin scattering (SBS). SBS results from an acoustic wave formed from the superposition of the propagating light wave and the counter-propagating stokes wave generated from the index modulation in the glass created by the propagating wave. The threshold power at which SBS occurs in single-mode fibers is given by

$$P_{Th} = 21.\frac{A_{eff}}{L_{eff}.g_B}$$

where $\mathbf{A_{eff}}$ is the effective area of the fiber, $\mathbf{L_{eff}}$ is the effective length of the fiber given by $\mathbf{L_{eff}=[1-exp(-\alpha L)]/\alpha}$, and $\mathbf{g_B}$ is the Brillouin gain coefficient. The larger core sizes (i.e. effective areas) of RE-LMA fibers lower the SBS threshold, compared to single mode fibers (by a few orders of magnitude) and enhance the power handling capability of the laser. RE-LMA fibers are often highly-doped with rare earth ions, such as Yb^{3+}, which increases the dB/m absorption. This increases the SBS threshold by decreasing the effective fiber length. It is noted that the gain coefficient depends on material properties including the acoustic velocity, density and the Brillouin gain linewidth. The Brillouin gain linewidth of bulk silica is reported to be 17 MHz, but it varies considerably in fibers, and significantly higher values are observed[8]. This can be attributed to compositional variations, as well as waveguide effects in the fiber which suppress the propagation of acoustic waves, and hence increase the threshold for SBS. In addition, the gain coefficient is also reduced at broad spectral linewidths.

To continue lowering the threshold of non-linear processes, one can either further reduce the core NA, increase the core diameter or increase the dopant concentration (to reduce the fiber length). The former becomes impractical, with silica inner claddings, since the bend loss of the fiber at the operating wavelengths increases exponentially. Increasing the dopant concentration runs the risk of inefficiency as quenching of fluorescence can occur. Increasing the core size, therefore, is the most beneficial. However, one may question how much of a core could be practically used for lasing/amplification. Concerns of overly-large core diameters include maintaining not only near single-mode operation, but a sufficiently large mode/core overlap, so that more of the Yb^{3+} ions can be utilized.

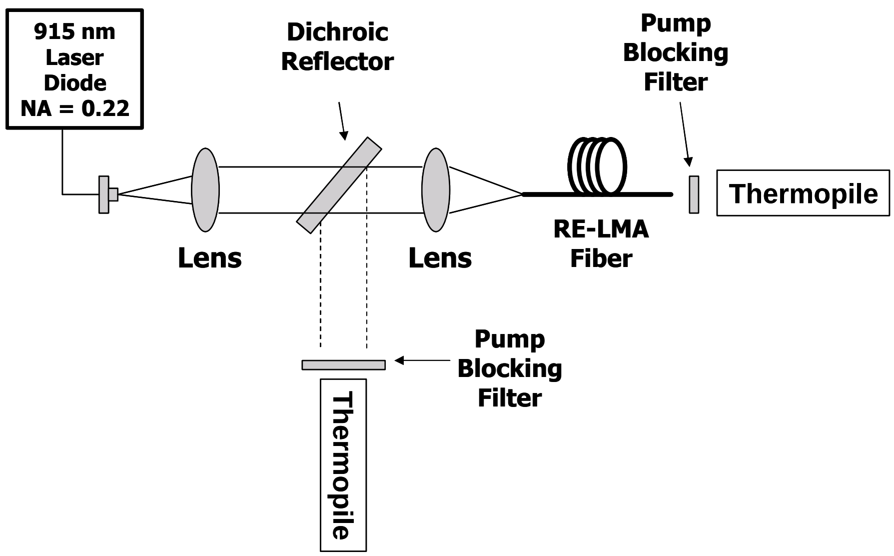
RE-LMA fibers generally have shaped inner claddings, to promote coupling of pump light into the core via scattering. This shaping is usually performed via a grinding procedure. PM versions (panda-type) have stress rods incorporated, which requires another mechanical preparation process. Incorporating these extra steps may influence the mechanical properties of the fiber, which is a concern for obvious reasons.

This paper investigates the aforementioned concerns of increasing core size on optical properties, as well as the effect of the manufacturing process of PM-double clad fibers on reliability. Optical measurements, on fibers of three different diameters, were performed to examine the effect of core size on beam quality. Mode field diameter measurements (or beam size for multimode fibers) were also performed and compared to modeled results. Additional modeling includes the calculation of SBS thresholds for these RE-LMA fibers for narrow linewidth conditions. Mechanical-reliability measurements were made on 125 micron DC fibers, with and without mechanical shaping and stress rod incorporation, to investigate the effect of these fabrication processes on the stress-corrosion factor n_d.

PROCEDURE

RE-LMA fibers were fabricated with the following dimensions (core/clad): 20/400, 30/250, 50/350. The 20/400 and 30/250 fibers were both PM fibers, while the 50/350 was non-PM. All fibers had a 0.06 core NA and 0.46 inner cladding NA. The cladding NA was measured using a Photon LD8900 3-D scanner and determined using points $1/e^2$ from the maximum). Slope efficiencies were measured to ensure each tested fiber had no pump coupling or quenching issues. The slope efficiency measurement is shown in Figure 1. A 915 nm LIMO laser diode (15W) was launched into a test fiber with two 4% fresnel reflectors. The total fiber absorption, at the pump wavelength, was approximately 13 – 14 dB. Power output was measured with an Ophir Optronics L30A thermopile power meter.

Figure 1 – Schematic of Slope efficiency measurement



M^2 measurements on coiled-fiber lasers were made using a Spiricon M2-200 beam propagation analyzer. The coiling technique, discussed by Koplow et.al[6], was used to reduce the number of transverse lasing modes in each fiber and stimulate single-mode operation. Fibers were coiled to different diameters (using mandrels) and both M^2 and beam sizes were measured on the laser emission from each coil size. Beam sizes were calculated using the measured size from the M^2 unit, corrected by the ratio of the focal lengths of the lenses used for collimation and focusing. For fibers operating with low M^2 values (1.1 or less) the beam size is assumed to be the MFD.

SBS modeling utilized equations currently available in the literature[8]. Calculation of MFD, using core diameters and NA, was obtained in a similar fashion. One issue with SBS modeling is the use of a Brillouin linewidth representative of a RE-LMA (type) fiber. As mentioned previously, the reported value of this linewidth does vary. Recently, the SBS threshold power of 108 W was reported for a 28 μm core Yb-doped LMA fiber, having a numerical aperture of 0.06[9]. Based on this value, the Brillouin linewidth used for the present SBS threshold calculations is estimated at 36.5 MHz.

Reliability testing was performed on two 5/125 fibers. The first had no mechanical alterations – no PM stress rods were incorporated nor was the cladding shaped. The second fiber had both a shaped cladding and Panda –style stress rods. Dynamic stress fatigue tests used to determine the n_d stress corrosion parameter for both fibers followed the Telcordia procedure TIA/EIA-455-28C (FOTP-28) "Measuring Dynamic Strength and Fatigue Parameters of Optical Fibers by Tension".

RESULTS

Table 1 shows the measured core NA, absorption (915 nm) and slope efficiency for the tested fibers. The 20/400 fiber had the lowest absorption, while the 30/250 and 50/350 fibers had around 3.5 dB/m absorption. The latter two fibers could be more suitable for small-linewidth or short pulse amplifiers, due to the shorter fiber-lengths required as a result of their larger absorptions. In all cases, the measured slope efficiency is over 70%, indicating low quenching.

Table 1 – Measured core NA, absorption and slope efficiency for tested RE-LMA fibers.

Fiber ID	Cladding Shape	Numerical Aperture	915 nm Absorption (dB/m)	Laser Slope Efficiency (%)
20/400 Yb PLMA	Octagon	0.06	0.55	73
30/250 Yb PLMA	Octagon	0.062	3.4	77
50/350 Yb LMA	Octagon	0.061	3.6	74

Table 2 shows the measured M^2 values and beam sizes for the tested RE-LMA fibers coiled to different diameters. Figure 2 shows a graph of M^2 vs. coil diameter for the tested fibers. Input pump power for these measurements was 7W at 915 nm. For the 20/400 Yb PLMA fiber, the beam quality is excellent (shown three-dimensionally in Figure 3), with M^2 values near or below 1.1 for coils down to 10 cm in diameter. Given the 20/400 fiber supports only 2 modes, it was fairly simple to coil out the LP_{11} mode. The measured MFD (beam size) for the LP_{01} mode was 19 microns, with the laser operating near 1080 nm. This is ~ 6% different than the modeled MFD of 18 microns and shows fairly good agreement. The overlap between core and MFD is approximately 67%.

Table 2 – Measured M^2 values and beam sizes for tested RE-LMA fibers

Fiber Type	Diameter of Coil (cm)	Fiber Length (m)	M^2_x	M^2_y	Measured MFD/Beam Size (microns)	Modeled MFD, LP_{01} (microns)
20/400 Yb PLMA	15	25	1.06	1.06	-	18
	10	25	1.09	1.13	19	
	8.9	25	1.09	1.09	-	
30/250 Yb PLMA	15	4.5	1.56	1.59	-	23.4
	6.3	4.5	1.38	1.66	-	
	5.5	4.5	1.11	1.13	25	
50/350 Yb LMA	15	4	2.95	2.92	45	35.6
	8.9	4	1.9	1.98	39/36	
	7.6	4	1.88	1.52	25/33	

For the 30/250 PLMA fiber, at a large diameter (15 cm) the M^2 value indicates multimode behavior. Given this fiber can support 5 modes, this is not unexpected. Decreasing the diameter to 6.3 cm, some improvement in the M_x value was measured, but the elliptical nature of the beam may indicate that the coiling condition did not remove helical polarities of the stripped modes uniformly. Coiling to 5.5 cm provided a single mode output beam with an M^2 near 1.1. For the LP_{01} mode (5.5 cm coil diameter) the measured MFD was 25 microns, approximately 7% different than the modeled value of 23.4 microns. The overlap between the core and MFD is approximately 76%, slightly larger than the 20/400 fiber. It is apparent that single mode quality can be achieved in the 30/250 fiber, with the possibility of achieving it somewhere between 5.5 cm and 6.3 cm coiling diameter.

The 50/350 LMA fiber exhibited a M^2 value of about 2.9 for the largest coiling diameter. Further reducing the coil size to 8.9 cm brought the M^2 value down below 2. At 7.6 cm, the M^2 measurement indicates some ellipticity in the beam, but the M_y is near 1.5. It is possible that M_x could be reduced to a similar number, once again, through sufficient coiling. These measurements do indicate that near-single mode beam quality may be achieved with the 50/350 fiber. It is noted, however, that the M^2 value increased with increasing power. This could be attributed to the possibility that higher order modes, present but at very low power compared to the lasing modes, began to lase as their lasing threshold power was exceeded. In observing the beam sizes measured, at each coiling size (and equivalent pump power), there is an obvious reduction in beam size with coiling. In fact, at 7.6 cm diameter, the beam size in one direction approaches 25 microns, which is a drop of ~ 20 microns in diameter from the 15 cm coil. Although this beam size decrease with coiling is expected, the active area of lasing emission does become quite a bit smaller than the core of the fiber. Therefore, the 50/350 fiber may not be the most suitable for single mode operation. Given the large size of the fiber core, however, which in this case has the capability of supporting 13 modes, the M^2 value at 15 cm coil diameter may be very suitable for higher power applications requiring slightly multimode beam quality.

Figure 2 – M^2 vs. Coil Diameter for tested fibers

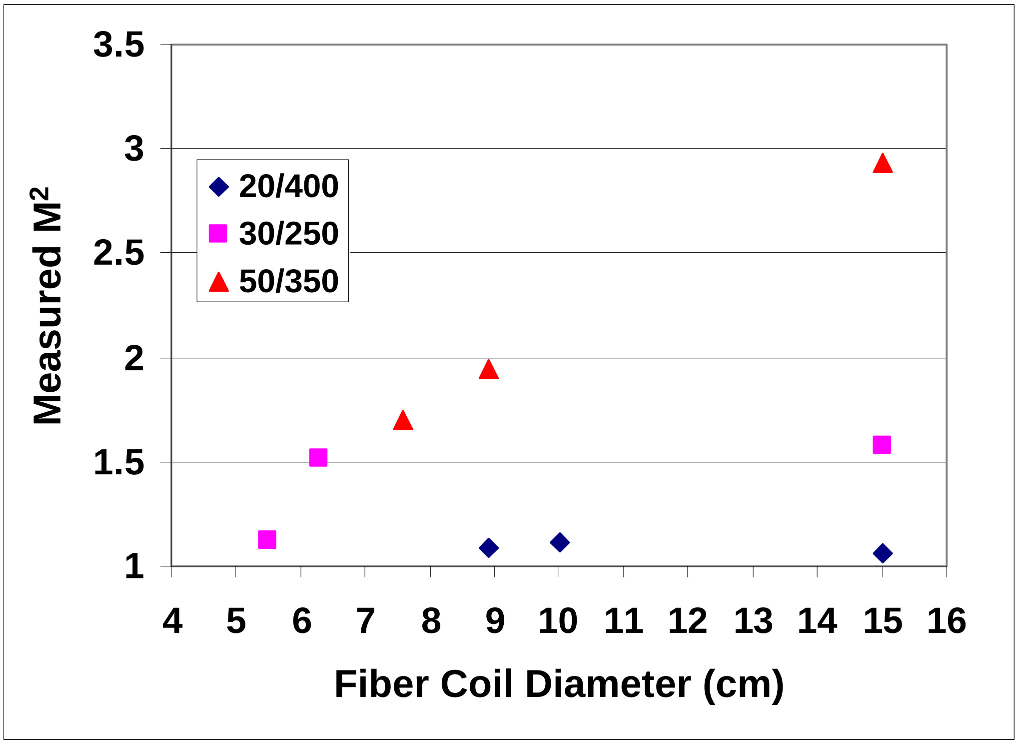
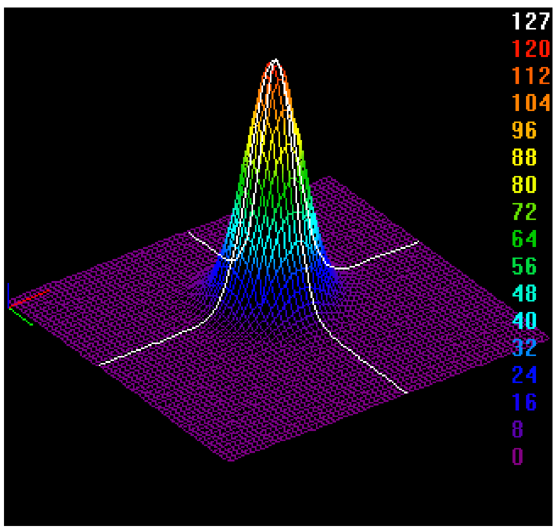


Figure 3 – Three-dimensional image of 20/400 laser output with 10 cm diameter coiling.



Modeling of SBS threshold as a function of core size (at various Brillouin linewidths) is shown in Figure 4. This modeling was based on the aforementioned 108 W result from the 28 micron core D-shaped Yb-DC fiber[9], in which 9.4 meters of fiber was used. Using the 36.5 MHz Brillouin linewidth estimated from this result, SBS threshold powers were calculated, for each of the test fiber geometries, at different pump wavelengths. Table 3 summarizes these calculations and includes calculations as well as for a single-mode Yb-doped fiber (core diameter of 5 microns).

Figure 4 - SBS threshold vs. core diameter for various Brillouin linewidths (Fiber NA=0.06 and length = 9.4 m)

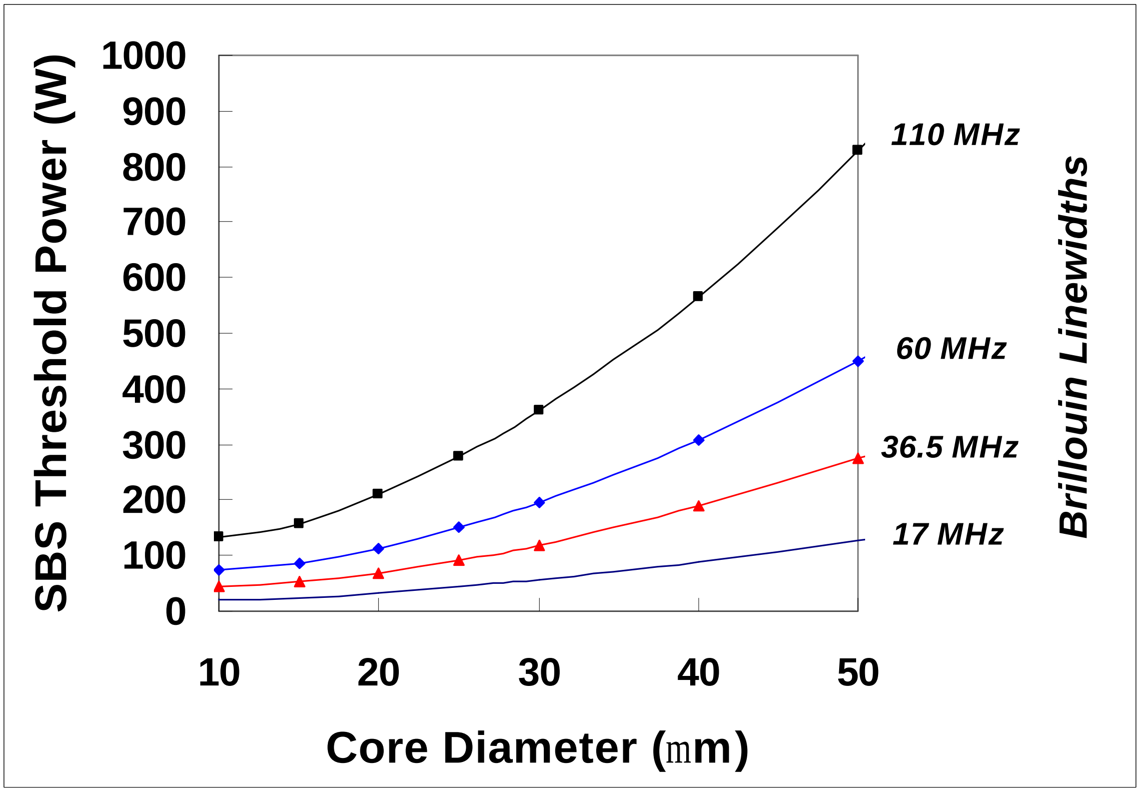
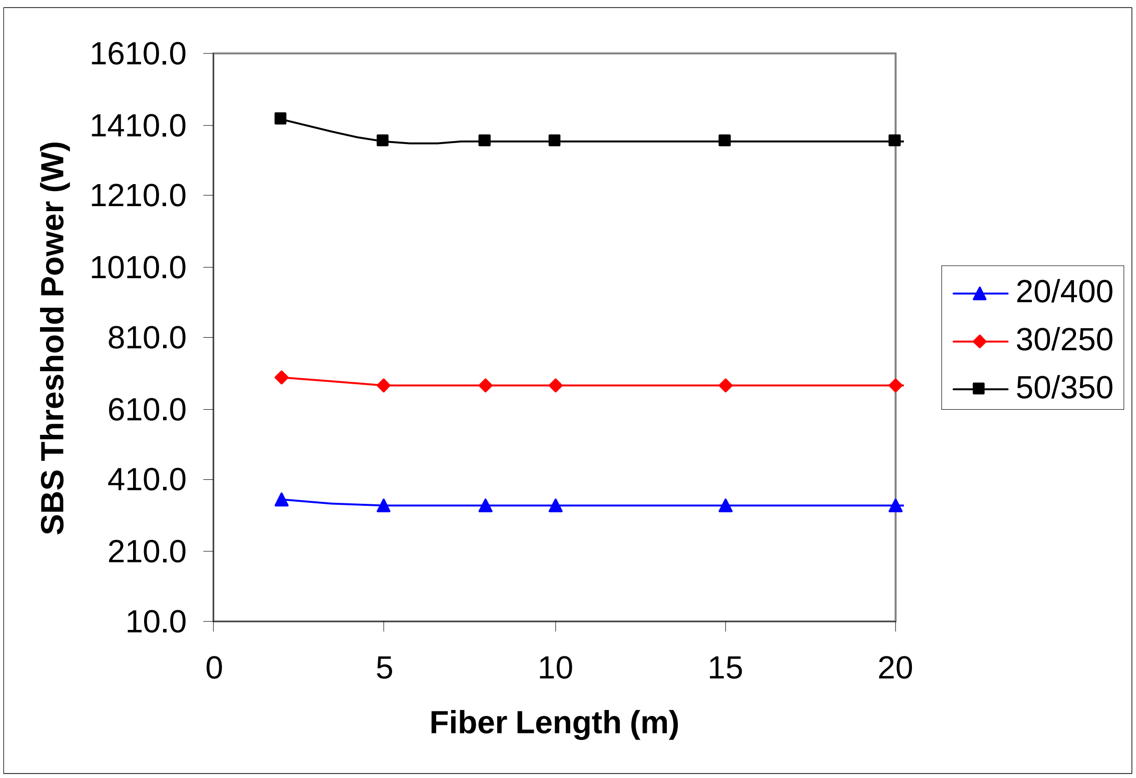


Table 3 – SBS threshold powers for various pump wavelengths for the single-mode and LMA fibers (at 3kHz pump spectral linewidth and 36.5 MHz Brillouin linewidth, 1064 nm wavelength)

F core (mm)	5	20	30	50
NA	0.151	0.06	0.062	0.061
Modeled Mode Field Diameter (1064 nm)	5.77	17.76	23.28	35.5
Modeled Overlap Integral (1064 nm)	0.54	0.72	0.81	0.86
1064 nm abs Estimate (dB/m)	7.18	6.57	7.75	6.71
L (m): 915 nm pump	25.5	25	4.5	4
Threshold Power (W): 915 nm pump	38.9	338.2	676	1363.4
L (m): 975 nm pump	7.7	7.6	1.4	1.2
Threshold Power (W): 976 nm pump	38.9	338.2	736	1613.2
L (m): 940 nm pump	43.3	42.5	7.7	6.8
Threshold Power (W): 940 nm pump	38.9	338.2	675.8	1360.6

The benefit of LMA fibers becomes obvious when comparing the power of SBS onset for single mode fibers and the large core fibers. For example, the single mode Yb-doped fiber with a 0.15 NA and a core diameter of 5 µm has an SBS threshold of ~ 39 W at 3 KHz linewidth when pumped at 915 m, while the 20 µm core 0.06 NA fiber has a threshold of ~338 W, and the 30 µm core 0.06 NA fiber has a threshold of 676 W. At 976 nm pump wavelength, the 30/250 fiber operate well over 700 W before the onset of SBS. In practice, the Brillouin pump linewidth can range from few KHz to several MHz, and hence the actual thresholds could be much higher depending on the system configuration. Although higher SBS thresholds are observed for shorter lengths of fibers (i.e. pumping at 976 nm), significant increases in threshold are not observed for the modeling of these fibers until the core diameter reached 30 microns. This is because the length of the fiber for the 30 and 50 micron cores, at 976 nm, is quite short (1-2 meters). As seen in Figure 5, the changes in SBS threshold are significant for fiber lengths shorter than 4 meters.

Figure 5 – SBS thresholds vs. fiber length for RE-LMA fibers (3kHz pump spectral linewidth and 36.5 MHz Brillouin linewidth).



.

Here, a distinction needs to be drawn between the amplifier configuration and laser configuration. The threshold values reported in Table 3 are relevant for amplification of fine linewidth signals, where the spectral linewidth is significantly lower than the Brillouin gain linewidth of 17-60 MHz. For laser configurations, the spectral linewidth may be 0.05 nm or broader, depending on cavity design. For example, the spectral linewidth with grating reflectors may be <0.1 nm, but with end-face polishing, it may be higher. In such situations, the SBS threshold is increased to >10 kW for the 20 mm core fiber, and other effects such as SRS and optical damage then become the limiting factors.

Figures 6 and 7 show the results of the dynamic stress fatigue tests performed on the non-PM and PM 125 micron double clad fibers. For reference, the Telcordia-specified minimum n_d value for passing the test is 18. For the non-machined fiber, the stress corrosion factor averaged slightly over 22, with a standard deviation of 0.25. This value is impressive in its own right, and a result of the clean environment in which the fiber is processed. The machined PM fiber, with shaped cladding and incorporated stress rods, was measured to have an equally large n_d of 22.69 (standard deviation of 0.20). These results are not significantly different (2-sigma) from the non-PM fiber and suggest that the processes of cladding shaping and stress rod incorporation have no detrimental effects on mechanical reliability. Future work will include the LMA fibers in such an analysis.

Figure 6 – Dynamic stress fatigue test on a 5/125 single mode DC fiber with no cladding shaping.

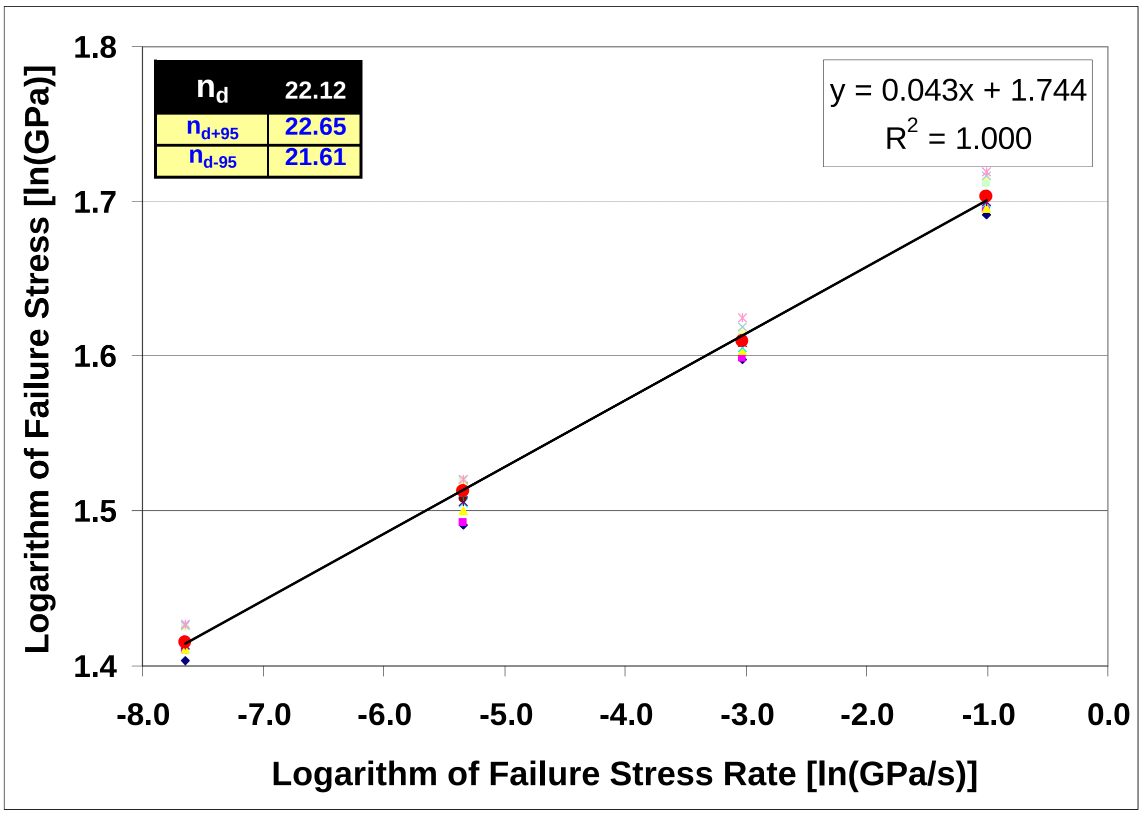
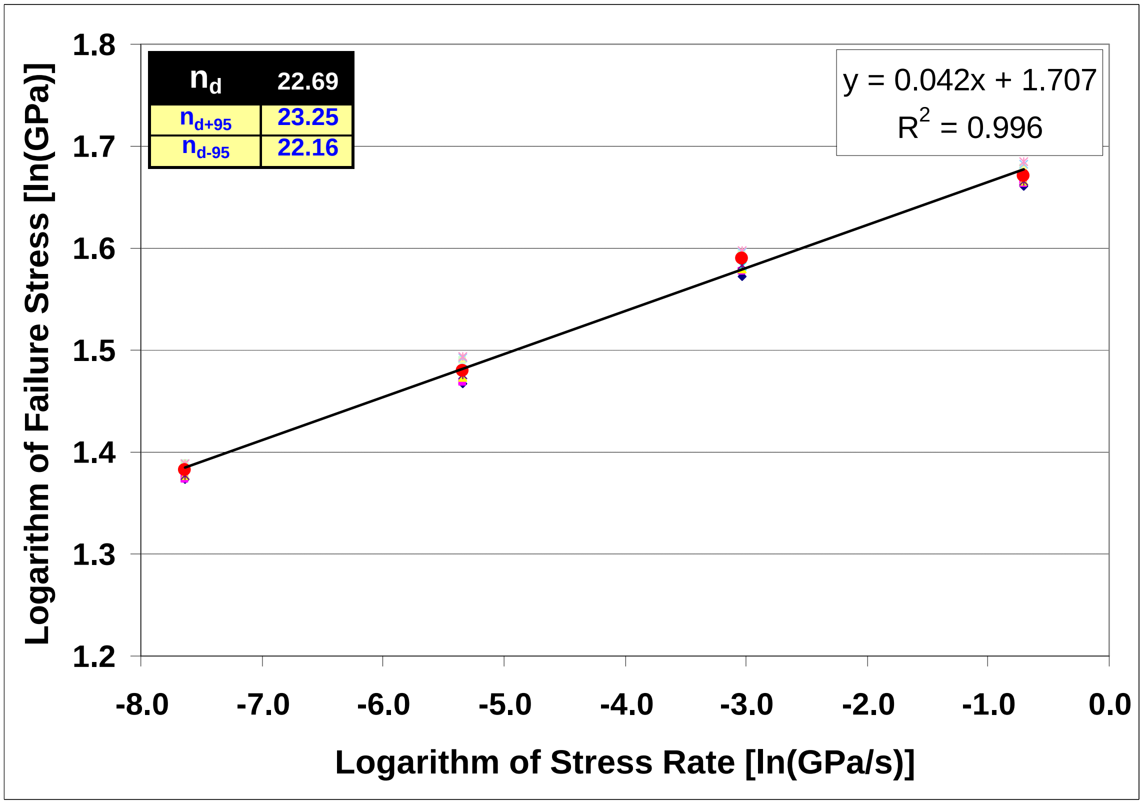


Figure 7 – Dynamic stress fatigue test on a 5/125 single mode DC fiber with cladding shaping and PM stress rod incorporation



SUMMARY

Rare earth doped, large mode-area (RE-LMA) fibers have been fabricated and tested in the lasing configuration, using different coiling diameters, for beam quality and beam size. Three fibers having 20, 30 and 50 micron cores where fabricated and measured to have > 70% slope efficiency. Both the 20/400 Yb PLMA and 30/250 Yb PLMA fibers were found to be operated single mode, following sufficient coiling, and exhibited M^2 values near 1.1. The 50/350 Yb LMA fiber, while not found to operate single mode, did exhibit M^2 values of 1.5 – 2.9 depending on coiling condition and could support a beam size near 45 microns. Modeling of SBS thresholds for these fibers indicate, for the 30 micron core fiber, > 700 W of narrow linewidth signal could be generated prior to the onset of SBS. Reliability testing on a pair of 125 micron DC fibers (shaped clad/PM and non-shaped clad/non-PM) showed the stress corrosion parameter n_d to not be statistically different (both fibers having $n_d > 22$). This result indicates no reduction in mechanical strength due to the clad-shaping and PM stress rod incorporation processes.

REFERENCES

1. Kanishka Tankala, Adrian Carter, David Machewirth, Julia Farroni, Jaroslaw Abramczyk and Upendra Manyam, "PM double-clad fibers for high power lasers and amplifiers", *Proceedings of SPIE – Advances in Fiber Devices,* **Vol. 4974, 2003**, pp. 220-229.
2. J. Limpert, A. Liem, T. Schreiber, H. Zellmer and A. Tunnermann, "Power and energy scaling of fiber laser systems based on Ytterbium-doped large-mode-area fibers", *Proceedings of SPIE – Advances in Fiber Devices*, **Vol. 4974, 2003**, pp. 135-147.
3. Michael Wickham, Dennis Hammons, Jesse Anderegg, Stephen Brosnan, Hiroshi Komine and Mark Weber, "High Power Fiber Array Coherent Combination Demonstration", *SSDLTR 2003 Technical Digest*, May, 2003, presentation HPFib-5.
4. S.J. Augst, A.K. Goyal, R.L. Aggarwal, T.Y. Fan and A. Sanchez, "Wavelength beam combining of ytterbium fiber lasers", *Optics Letters***, Vol. 28, No. 5**, March 1, 2003, pp. 331-333.
5. Roy D. Mead, Anping Liu, Tracy Vatter, Angus Henderson, "High-Power Spectral Beam Combining of Fiber Lasers", *SSDLTR 2003 Technical Digest,* May, 2003, presentation HPFib-3.
6. 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.
7. M. E. Fermann, "Single-mode excitation of multimode fibers with ultra-short pulses," *Optics Letters*, **23(1)**, 52-54, 1998.
8. **Non-linear Fiber Optics**, G.P. Agrawal, 2nd Ed. Academic Press 1995.
9. A. Liem, J. Limpert, H. Zellmer and A. Tunnermann, "100-W single-frequency master-oscillator fiber power amplifier," Optics Letters v. 28, n. 17 (2003) 1537-1539.