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

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Rare-Earth doped, Large Mode Area (RE-LMA) Double Clad Fibers

• Fibers specifically designed to convert low brightness, relatively inexpensive light sources to high brightness sources with good beam quality ($M^2 \sim 1$).

• Fibers doped with Ytterbium (Yb^{3+}) due to close proximity of pump (915-975 nm) and emission (1060-1110 nm) wavelengths of Yb^{3+}.

• LMA fibers doped with Yb^{3+} exhibit large slope efficiencies (> 75%).

• Published results using RE-LMA fibers report CW operation of >> 100 W and pulsed operation > 1 mJ.

• Beam-combining techniques could produce lasers > 1 kW with good beam quality.

• Advances in fabrication of RE-LMA fibers (PM and non-PM) have enabled the production of standard products.

Limiting Mechanisms of Output Power For A Fiber Laser/Amplifier

1. ***Amplified Spontaneous Emission (ASE)*** – reduces gain at the signal/lasing wavelength by utilizing stored energy within the fiber during amplification of fluorescence.

Reduce ASE captured by the core by ↓ core NA

2. ***Stimulated Brillouin Scattering (SBS)*** – scattering of laser/amplifier emission by an acoustic wave formed between the propagating wave and a counter-propagating stokes wave. SBS threshold most sensitive to narrow linewidths (ex. 3kHz).

$$P_{Th,SBS} = 21 \cdot \frac{A_{eff}}{L_{eff} \cdot g_B}$$

P_{th} = SBS Threshold power
A_{eff} = Effective area of the core
L_{eff} = Effective Length of the fiber
g_B = Brillouin gain coefficient

Reduction of SBS threshold by either: **Decreasing fiber length OR increasing core area**

RE-LMA Fiber Design Considerations

• Continually decreasing fiber core NA becomes impractical due to the severe bend loss increase resulting from NA change (practical core NA ~ 0.06).

• Fiber length ↓ requires Yb^{3+} concentration ↑. Worry about effects of quenching, as well as increase in NA with more rare earth incorporation.

• Increasing core size represents most practical method to decrease SBS threshold.

How large in core size is practical for single mode operation? Effect of core size on SBS Threshold?

Procedures for Present Investigation

Core Size Investigation

- *Fabricate fibers to three different diameters (similar core NA)*
- *Test fibers for slope efficiency (lasing configuration)*
- *Measure M^2 (beam quality) on fibers coiled to different mandrel diameters**
- *Measure beam size (using M^2 measurement).*
- *Model SBS thresholds for all three diameters under a narrow linewidth condition*

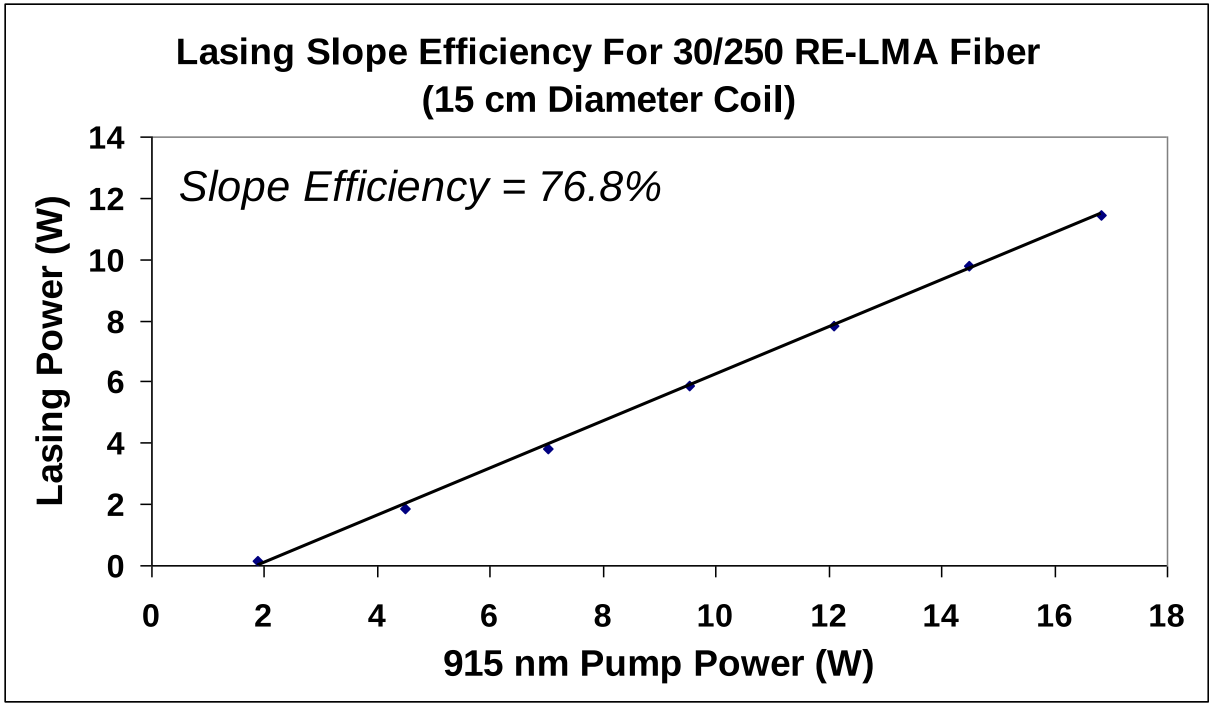
Reliability

- *Fabricate two 5/125 DC fibers*
  - ***Fiber A**: no cladding shaping, no stress rod incorporation*
  - ***Fiber B**: shaped cladding, PM (stress rod incorporation)*
- *Perform dynamic stress fatigue tests on each fiber to obtain Telcordia n_d value*
- *Compare results*

Koplow, et. al, Optics Letters 25(7), 442-444, 2000

Fabricated-Fiber Parameters

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

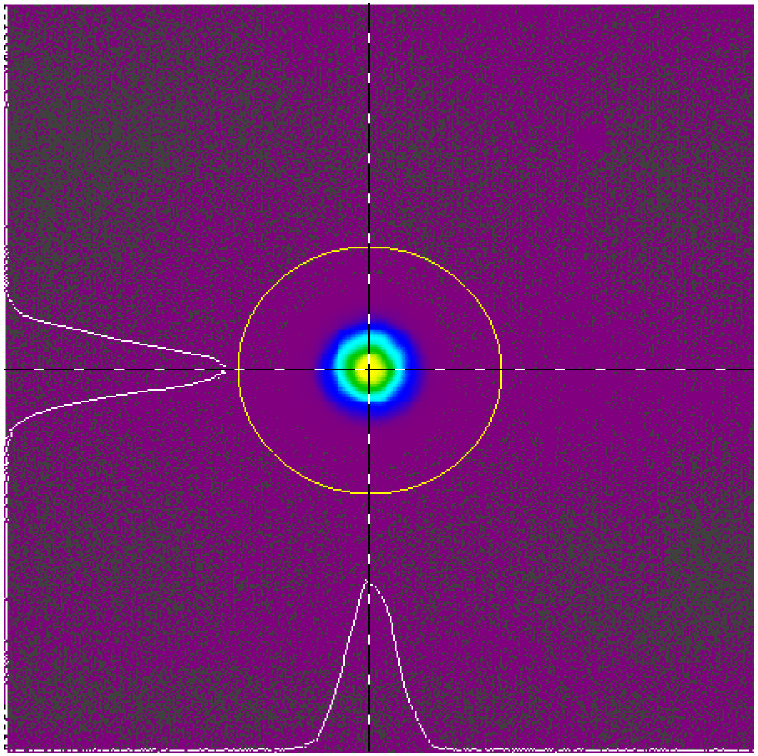


M^2 and Beam Size Measurements

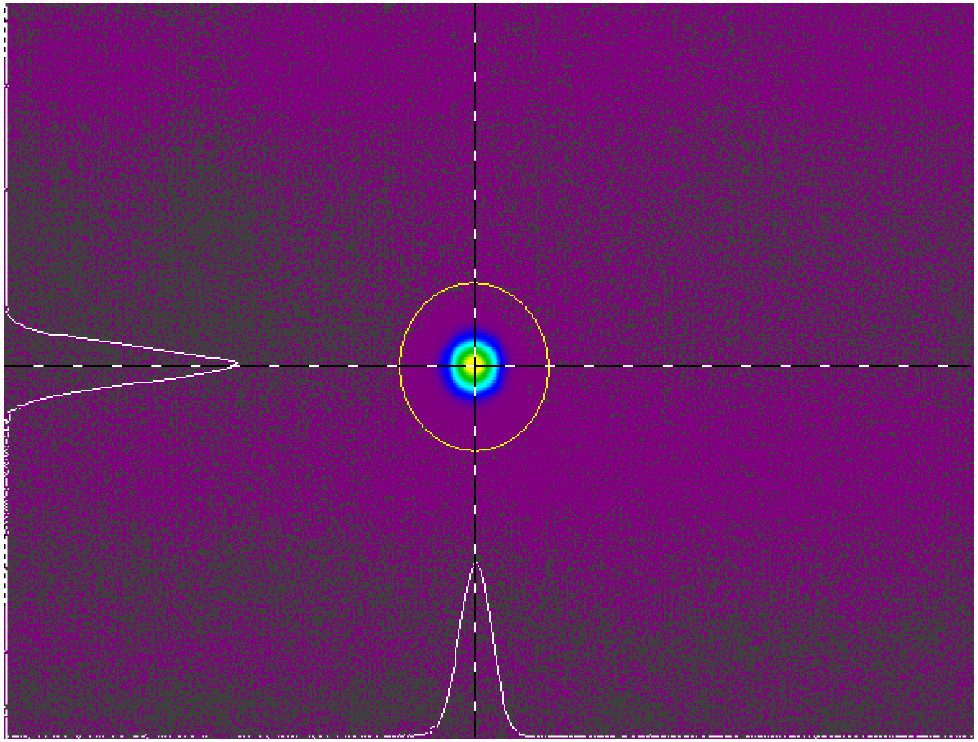
Fiber Type	Diameter of Coil (cm)	Fiber Length (m)	M^2_x	M^2_y	Measured MFD/Beam Size (microns)	Modeled MFD, LP_{01} (microns)
PLMA-YDF-20/400	15	25	1.06	1.06	-	18
	10	25	1.09	1.13	19	
	8.9	25	1.09	1.09	-	
PLMA-YDF-30/250	15	4.5	1.56	1.59	-	23.4
	6.3	4.5	1.38	1.66	-	
	5.5	4.5	1.11	1.13	25	
LMA-YDF-50/350	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	

- All measurements performed at same pump power (7W @ 915 nm)
- 20/400, 30/250 capable of SM operation
- 50/350 M^2 ~ 2.9 with large coil, possible 1.5 with better coiling?
- 50/350 M^2 increased (> 2) with increasing power (7.6 cm) – lasing of higher order modes present (but below threshold) for coil size?

Mode Quality Measurements

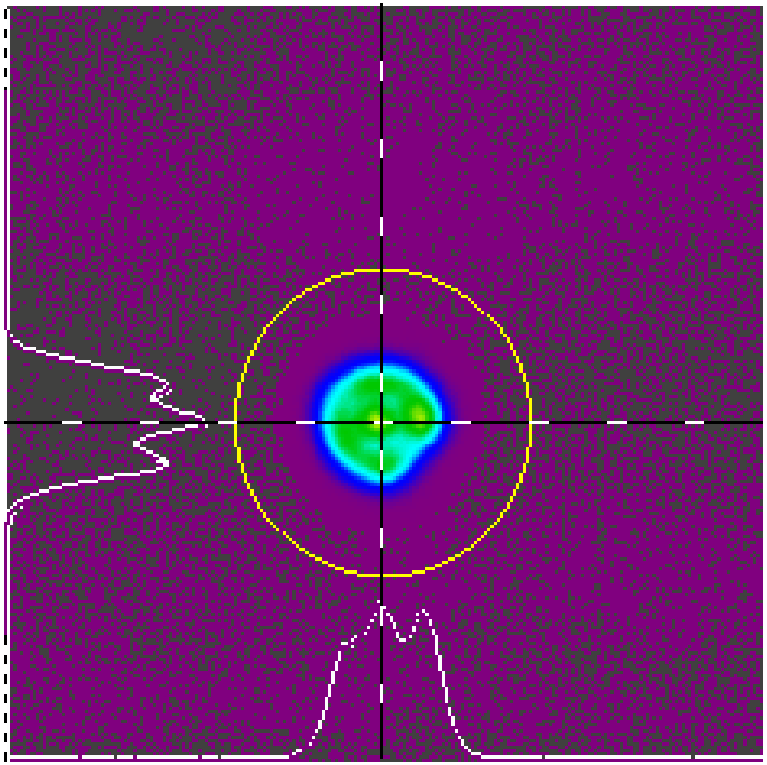


20/400 PLMA
10 cm coil
$M^2 \sim 1.1$

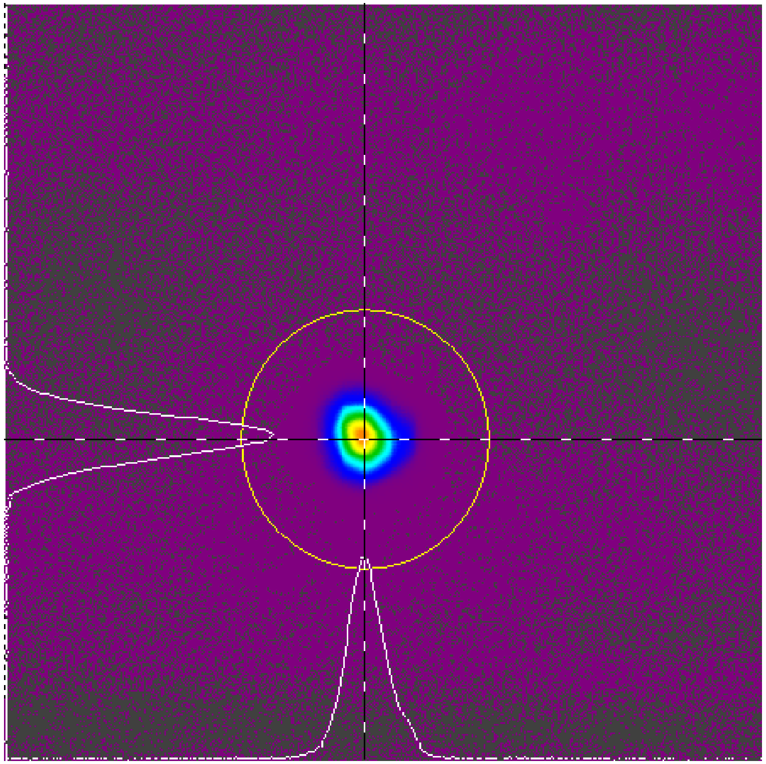


30/250 PLMA
5.5 cm coil
$M^2 \sim 1.1$

Mode Quality Measurements (continued)

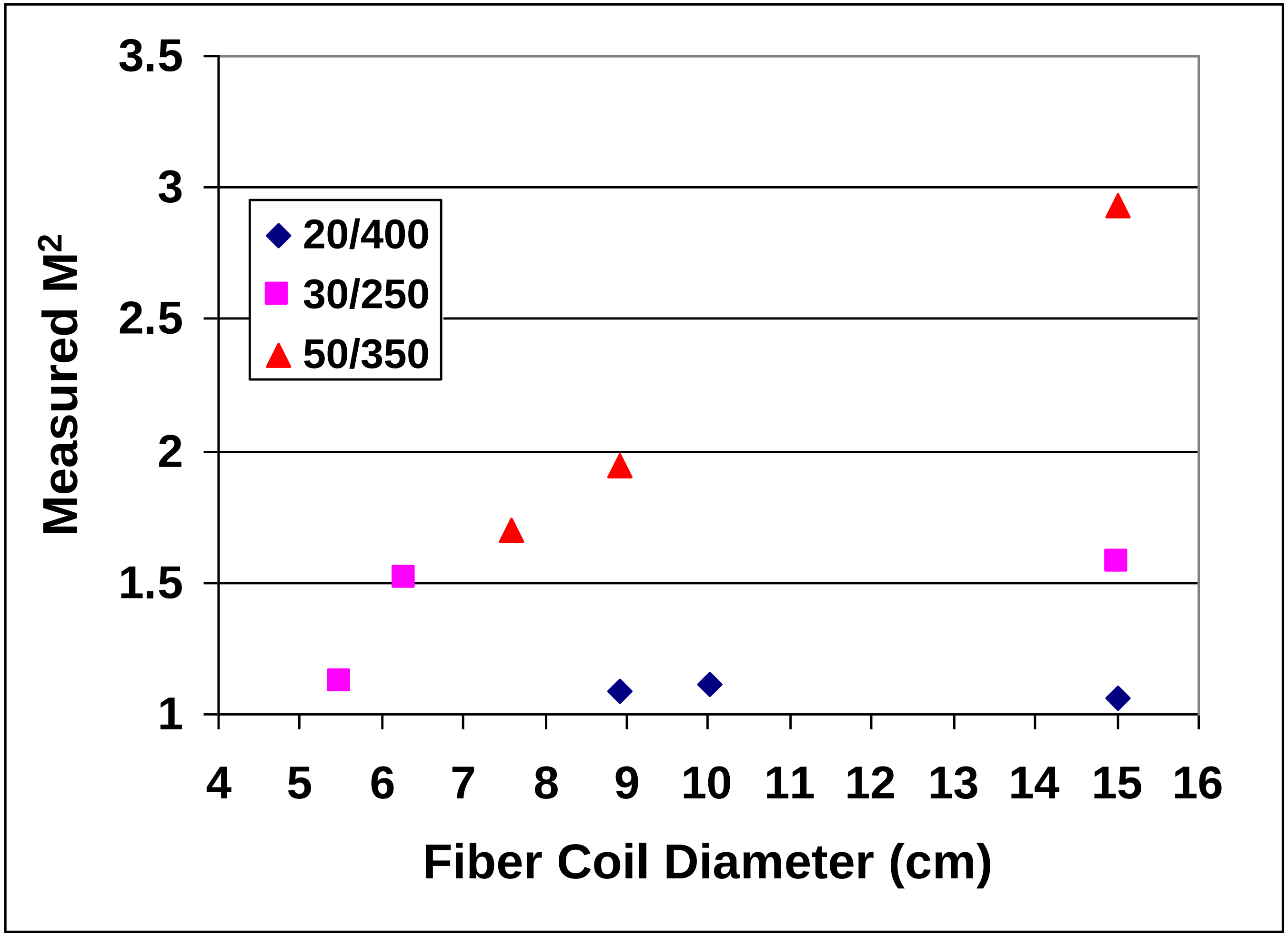


50/350 LMA
15 cm coil
M^2 ~ 2.9



50/350 LMA
7.8 cm coil
M^2 = 1.5/1.9

M^2 vs. Coiling Size For Tested Fibers



50/350 LMA Fiber predicted to operate near single mode at ~ 4 cm.

Modeling of SBS Threshold Powers

• Modeling requires a value for the Brillouin linewidth for a Yb-Doped LMA (range of values reported in the literature)

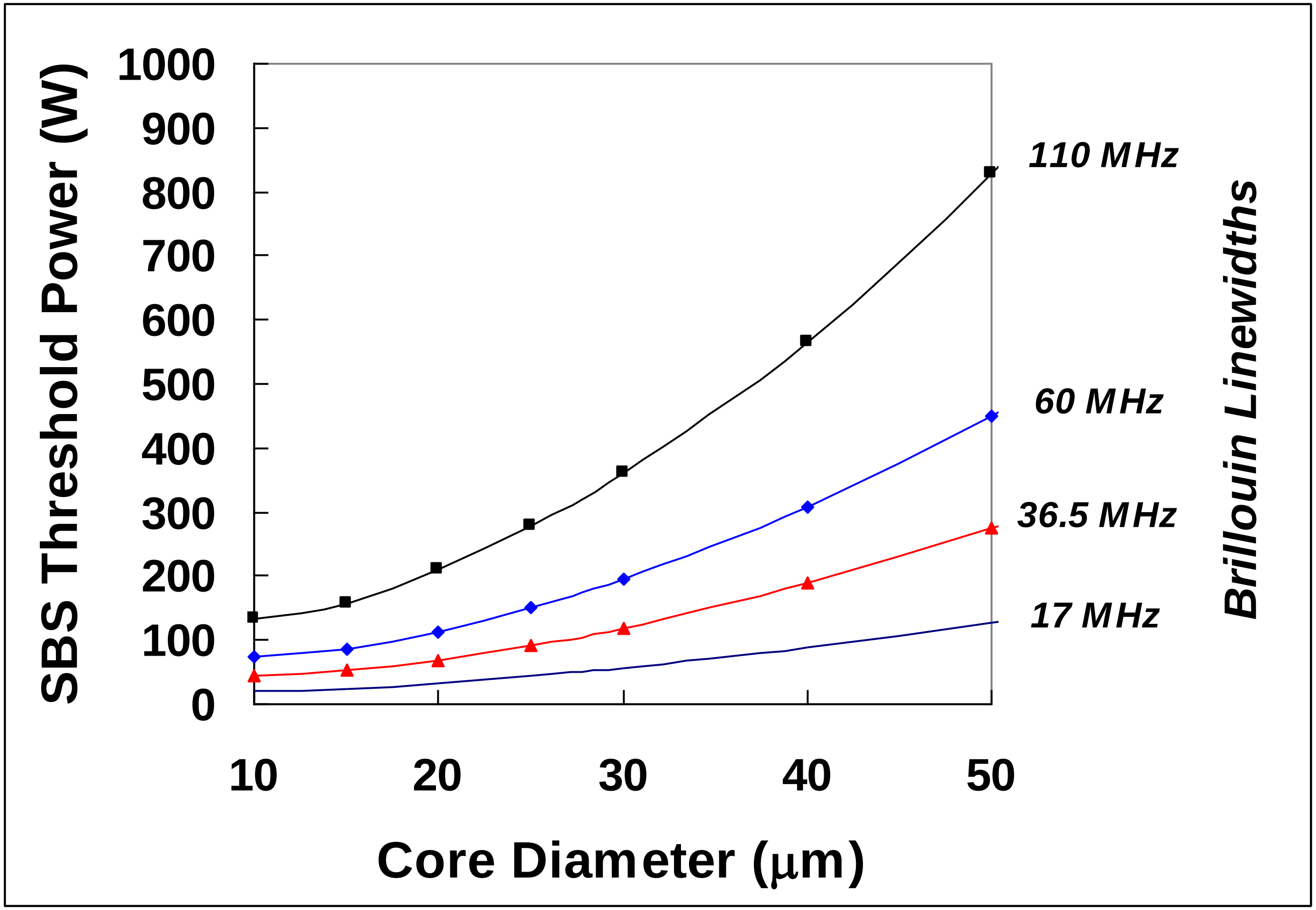
• 108 W amplified signal (narrow linewidth) measured from a D-shaped Yb-doped DC fiber, with a 28 micron core.

• Calculated Brillouin linewidth (using assumed geometrical factors) was between 17 - 36.5 MHz. Included assumptions regarding:

  - Fiber Absorption at pump wavelength (9.4 m with 976 diode)
  - Cladding area (D-shaped fiber)
  - Width of Diode (apparent absorption vs. measured spectral absorption)

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.

Modeled SBS Threshold Powers vs. Core Diameter for Various Linewidths



Fiber length = 9.4 m, Fiber NA = 0.06, Pump Linewidth = 3 kHz

Modeled SBS Threshold Powers at 1064 nm (SM and LMA)

- 1064 nm is a common wavelength for amplification
- Narrow linewidth of input signal assumed (3 kHz)
- Brillouin Linewidth = 36.5 MHz
- Modeled MFD and overlap integral between SM and core

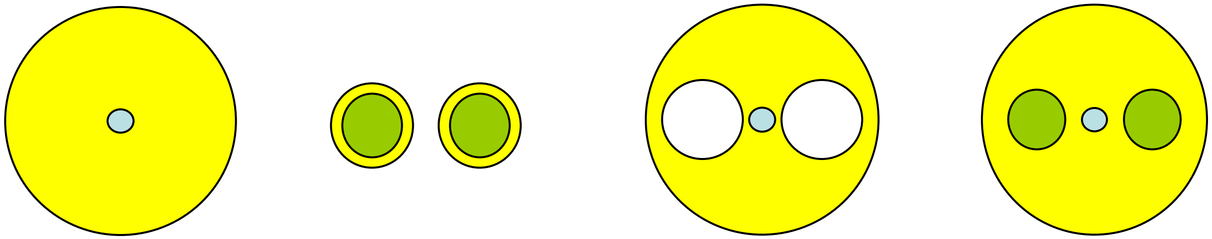
Φcore (μm)	5	20	30	50
NA	0.151	0.06	0.062	0.061
Modeled Mode Field Diameter (1064 nm)	5.77	17.76	23.28	35.5
Modeled Overlap Integral (1064 nm)	0.54	0.72	0.81	0.86
1064 nm abs Estimate (dB/m)	7.18	6.57	7.75	6.71
L (m): 915 nm pump	25.5	25	4.5	4
Threshold Power (W): 915 nm pump	38.9	338.2	676	1363.4
L (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

- *SBS threshold > 700 W for 30 μm core (976 nm), > 1600 W for 50 μm core*
- *Increases in SBS threshold, via decreasing length, occur when L < 4 m.*
- *For 17 MHz, threshold powers are roughly half that at 36.5 MHz.*

Achievable Powers…

- Modeled powers for narrow signal linewidths
- Larger signal linewidths (3 kHz) will further increase SBS threshold.
- Output powers > 500 W achieved using LMA-YDF-20/400.
- Power limiting mechanisms such as SRS and material damage are more likely at these linewidths.

RE-DC Fiber: Fabrication Processes



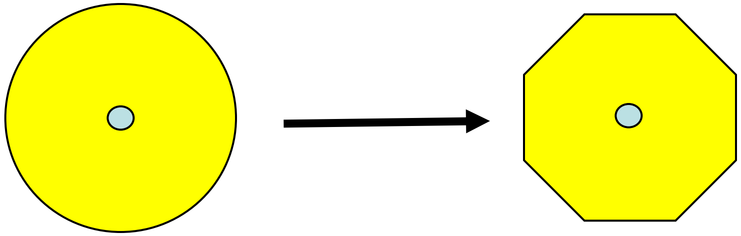
Manufacture Standard Preform

Manufacture Stress Rods

Drill Holes

Insert Stress Rods and Draw

K. Tankala, et al, LASE 2003 Presentation

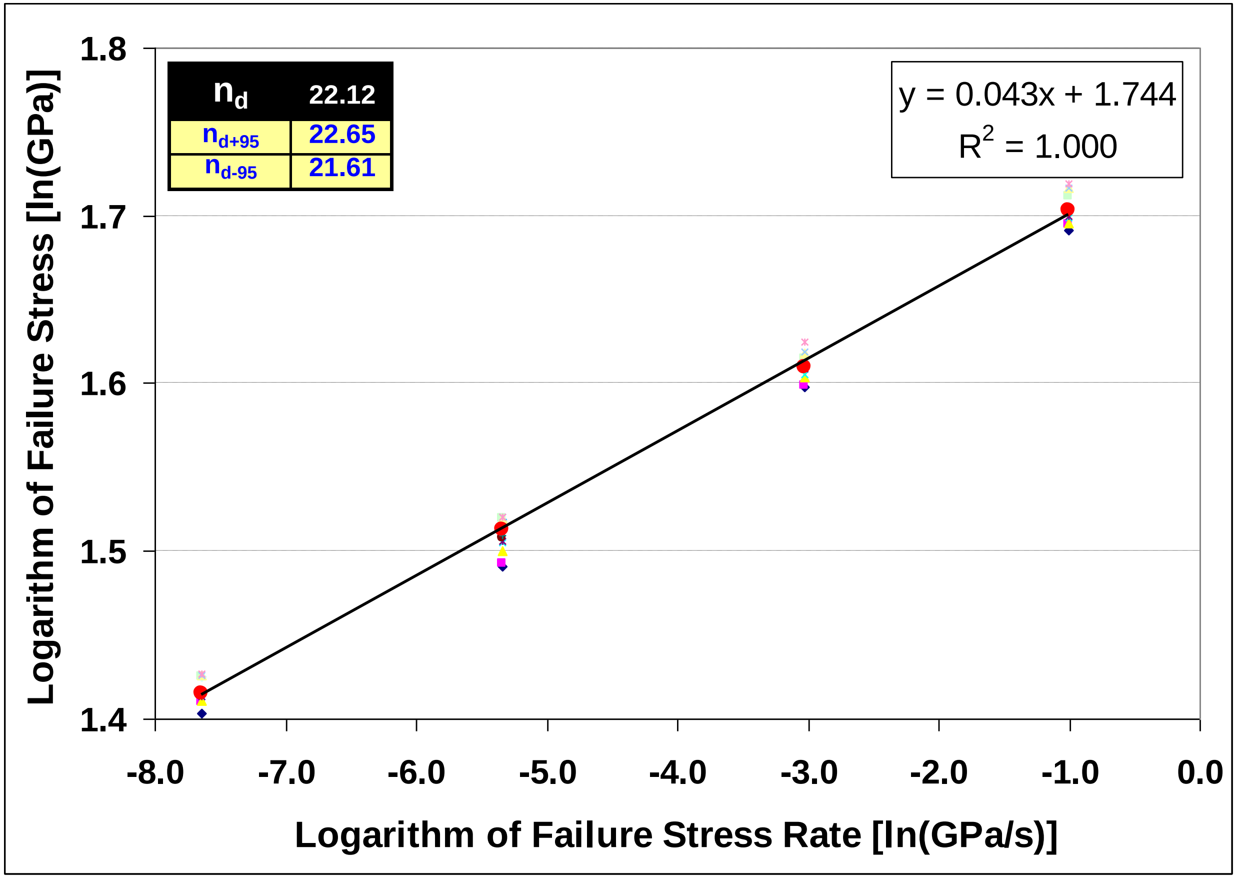


Manufacture Standard Preform

Shape Inner Cladding of Preform

How do these processes affect the reliability of the RE-DC fiber?

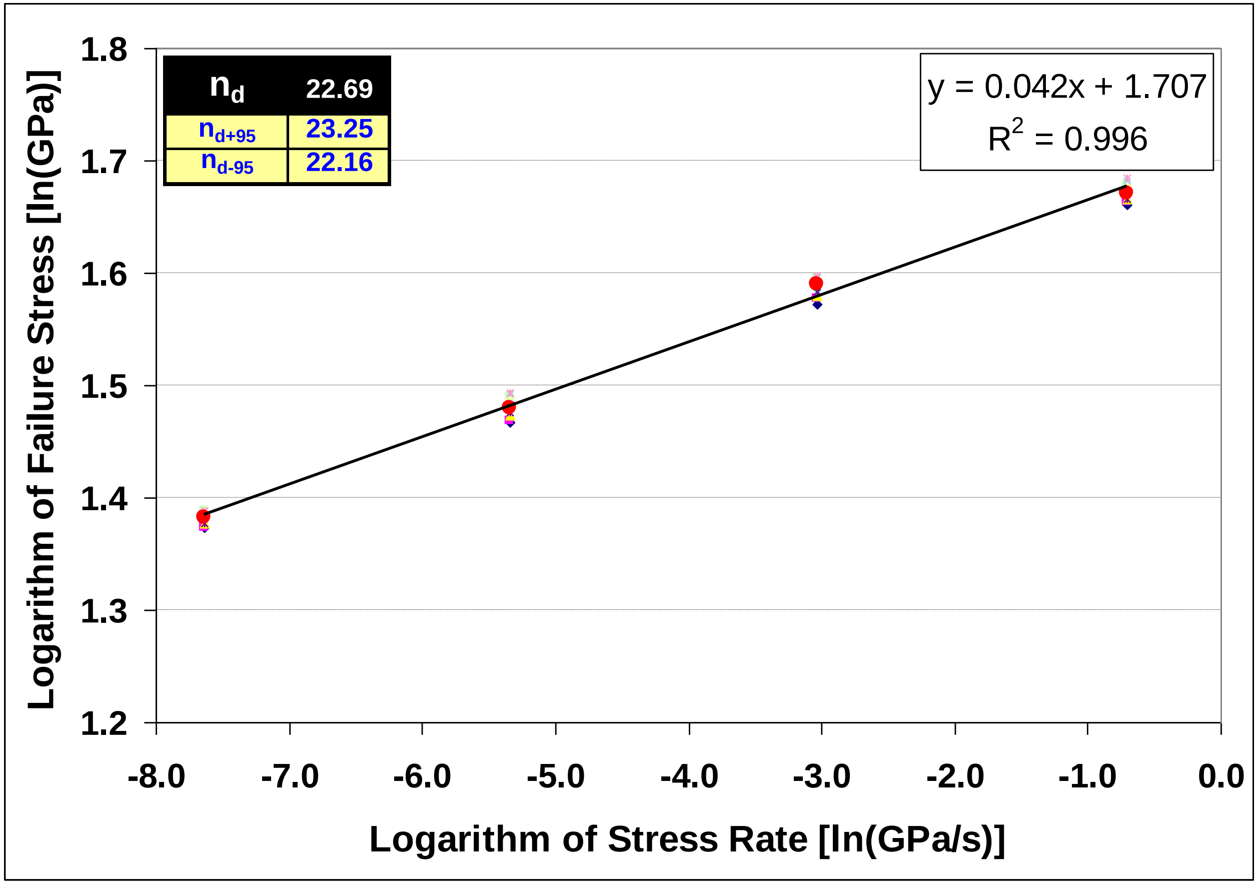
Dynamic Fatigue Tests – Non-shaped, Non-PM 5/125 DC Fiber



- *Followed Telcordia procedure TIA/EIA-455-28C (FOTP-28)*
- *Stress Corrosion Resistance Parameter n_d> 18*
- *Measured n_d > 22*

•n_d on 1060HP fiber
•(standard acrylate) is ~ 29. Indicates some reduction in failure stress caused by low index coating.

Dynamic Fatigue Tests – Shaped Cladding, PM 5/125



- Equally impressive n_d value
- Not statistically different than non-shaped, non-PM fiber
- Indication that preform processing does not affect fiber reliability
- Future work to be performed on larger-cladding fibers

Summary

• RE-LMA fibers with 20, 30 and 50 micron core sizes fabricated.

• 20/400 and 30/250 achieved single mode (lasing configuration) via coiling.

• 50/350 has M^2 between 1.5 – 2.9, single mode operation estimated to be 4 cm (possible reduction in efficiency?). More investigation required for higher power operation.

• SBS threshold modeling shows tested RE-LMA fibers capable of output powers > 150 W (17 MHz), >300W (36.5 MHz) at very narrow linewidths (3 kHz signal).

• SBS thresholds for larger linewidths are much greater (> 1 kW).

• Low-index coating reduced n_d compared to standard acrylate.

• RE-LMA Fiber fabrication processes (clad shaping, stress rod incorporation) were found not to reduce strength of 5/125 DC fibers.