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Short Length High Gain ASE Fiber Laser at 1.54μm by High Co-doped Erbium and Ytterbium Phosphate Laser Glasses

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Abstract

Ytterbium only and erbium-ytterbium co-doped phosphate glass Double Clad (DC) cladding pumped Large Mode Area (LMA) core fibers are manufactured at Kigre by the "rod-in-tube" method. The ytterbium and erbium doping concentration levels in phosphate glass are as much as two orders of magnitude higher than the doping concentrations found in fused silica fiber manufactured by Modified Chemical Vapor Deposition (MCVD) method. The background loss of the fiber's core and cladding measured ~ 0.01 dB/per cm at 1310nm. The measured absorption coefficient at 974 nm is 0.3 dB/per cm for the ytterbium-erbium co-doped fiber. Greater than 4.6 Watts CW laser output was demonstrated from the Er:Yb:glass fiber at 1535nm with a 37.4% slope efficiency and 36.3% optical efficiency. The Yb:glass fiber produced a maximum output power of 1.6 Watts in a 14cm gain length.

Introduction

Phosphate glasses are attractive laser oscillator/amplifier materials because unlike silica and other laser host materials they combine many attractive properties such as good chemical durability, ion-exchangeability, readily clad-able, high gain, low concentration quenching, and low up-conversion losses. Phosphate glasses also exhibit very high solubility for rare earth ions. This allows for the introduction of large concentrations of active ion into relatively small mode volumes resulting in smaller laser devices with high-energy storage capabilities.

In this paper we report on short length high gain phosphate glass ASE fiber laser performance. The fiber samples are cladding pumped LMA, DC multimode phosphate glass doped with ytterbium or co-doped erbium and ytterbium. The ytterbium and erbium doping levels are orders of magnitude higher than found in MCVD silicate fibers. Fibers with various gain length from 17cm to 72cm were evaluated. Our test data includes measurement of background loss, absorption at pumping wavelength and numerical aperture (NA).

DC LMA Phosphate Glass Fiber Properties

For these experiments, we selected double clad or "cladding pumped" samples of ytterbium only fiber with a 400 μm x 400 μm glass cladding with a 25 μm core. The refractive index of the Yb:glass fiber core is 1.530, cladding is 1.522, and acrylic overcoat 1.398. The sample Er:Yb:glass fiber exhibits a 250 μm x 250 μm glass cladding with a 15 μm core. The refractive index of the Er:Yb:glass fiber core is 1.535, cladding is 1.532, and acrylic overcoat 1.398.

Background Losses

We probed the DC LMA fiber samples with a 1310nm diode laser coupled into a standard Corning SMF-28 single mode delivery fiber to measure the optical background losses. The core diameter of SMF-28 fiber is 8 μm. This allows us to inject the 1310nm laser power into the core and cladding independently. Table 1 presents the average (10 pcs) background losses measured on the fiber's core or cladding [1].

	10 cm Fiber Transmission		
	Maximum	Minimum	Average
Core	0.989	0.957	0.970
Cladding	0.990	0.946	0.977

Table 1 Background loss for DC LMA fiber

The transmission measured for fiber's core and cladding are nearly the same. 0.977 transmission through 10cm of fiber corresponds to ~0.01dB/cm loss. This loss value is significantly higher than that of standard silica fiber. However, the effective fiber laser gain length is orders of magnitude shorter for phosphate glass due to the higher rare earth ions/cc doping levels. This translates into much higher laser energy storage and extraction values. For example, it takes **14 meters** of erbium-doped silica fiber to generate a gain of 40 dB [2]. Yet, we have demonstrated 38 dB of gain in only **13 centimeters** of erbium doped QX fiber with the same core diameter and as much as 47dB in 15.4cm [2,3].

Transmission at the Pump Wavelength

We utilized a Boston Laser 200μm diameter fiber coupled 975 nm diode array as a pump source for most of our experiments. The small diameter pump delivery fiber provides excellent coupling into our Er:Yb:glass 250 μm x 250 μm fiber cladding. Using this pump we obtained a maximum optical efficiency of 36.3% assuming nearly all the pump power was effectively captured & contained in the laser fiber. We calculated the transmission of laser fiber at the pump wavelength by measuring leftover pump power at output end of the laser fiber. Table 2 shows a typical set of test data.

Pump Power Absorption Calculations
27.8 cm Fiber Length

I	Pump	1.54 ASE	Total Power	True ASE	Leftover Pump	T	Peak Wavelength
0.5	0.72	0.038	0.261	0.042222	0.218778	0.303858	968.5
1	2.4	0.221	0.835	0.245556	0.589444	0.245602	969.5
1.5	4.06	0.457	1.295	0.507778	0.787222	0.193897	970.4
2	5.75	0.676	1.773	0.751111	1.021889	0.17772	971.3
2.5	7.41	0.912	2.12	1.013333	1.106667	0.149348	972.3
3	9.15	1.172	2.62	1.302222	1.317778	0.144019	973.5
3.5	10.9	1.38	3.15	1.533333	1.616667	0.148318	974.4
4	12.7	1.55	3.77	1.722222	2.047778	0.161242	976.1
4.5	14.4	1.65	4.55	1.833333	2.716667	0.188657	

Table 2. Calculated transmission of Er:Yb:glass fiber at the pump wavelength

Attenuation at the Pump Wavelength

Fiber up-conversion fluorescence and Amplified Spontaneous Emission (ASE) is readily produced and observed with effective coupling of relatively low 975nm pump powers into the DC LMA Er:glass. High intra-cavity power density and gain in the fiber leads to laser action occurring without external laser resonator optics (fiber end-face Fresnel reflections only). In order to measure the attenuation at the pump wavelength we separated the ASE and measure it. The third column in table 2, "1.54 ASE" is the measure of the 1.54 ASE output power with a dual band coated mirror that blocks the pump power at 975 nm and passes the 1535nm ASE output though with 90% transmission. The fourth column "Total Power" is a measure of the total power emitted from one end of the fiber. Normally, this consists of the pump power at 975 nm and ASE power at around 1535nm. We calculate the un-absorbed pump power, as "Leftover Pump" shown in column 6 and the fiber transmission "T" at pump wavelength. Numerous fiber samples were tested with various fiber lengths. The results show that the fiber transmission T changes with pumping current and exhibits a minimum value at ~3 Amps of pump current.

Using an AQ-6315E Optical Spectrum Analyzer (OSA) manufactured by ANDO, we measured the output spectra from pump diode. This data is shown below in figure 1 and figure 2.

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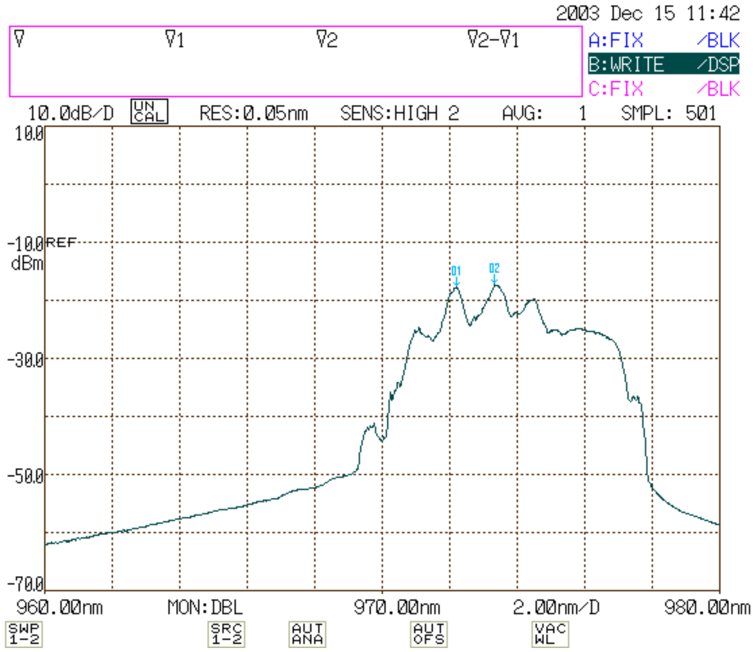

Fig. 1 Diode output @ 3-Amps pump current

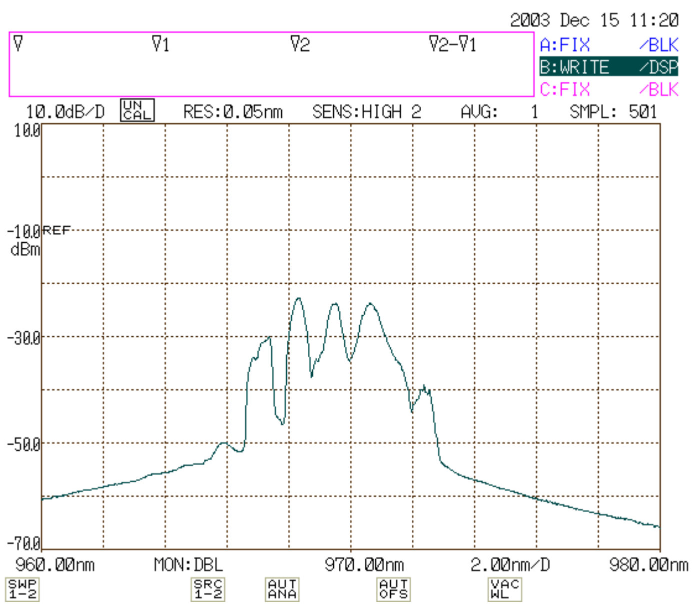

Fig. 2 Diode output @ 0.5-Amps pump current

The pump laser array contains six individual laser diode emitters in linear series or stripe. We observe that each diode has a different emission peak that shifts with changes in pump current. Figure 1 and Figure 2 correspond to 3 Amps and 0.5 Amps pumping current respectively. The data indicates that the best absorption match between absorption band of the glass and the pump diode's emission wavelength is found at the 3

Amp pump current level. This corresponds to an optimum pump wavelength of about 974nm

Absorption measurment results are shown in table 3 below.

Pump Absorption Measurements @ 974 nm

Length (cm)	Method	T	dB/cm
24	Direct	0.1932	-0.2975
20	Direct	0.2135	-0.3353
17	F=4.6	0.2969	-0.31023
27.8	F=4.6	0.144	-0.30275

Table 3. Pump Absorption Measurements @ 974 nm

The 27.8 cm long fiber sample exhibits a transmission of 0.144 for 975 nm pump wavelength. This corresponds to $(1/e^2)$ or 86.5% transmission and is very close to the optimum absorption length for this fiber design.

Erbium and Ytterbium co-doped fiber Experiments

We experimented with various optic lens systems to facilitate pump launch into the fiber end face. These included single lens and two lens systems with different focal lengths. The best results were demonstrated with direct pumping via fiber-coupled diode arrays.

Figure 3 shows the fiber laser laboratory setup. Note the green upconversion from the Er^{+3} $^2H_{9/2}$– $^4I_{13/2}$ transition. In references [5] & [6] weak erbium phosphate glass upconversion emission was measured in two green bands (520nm & 543nm), a red band (650nm) an infrared band (780-850nm), and a number of UV bands (361nm, 405nm and 450nm). The intensity of the different bands is dependent upon the pump intensity and erbium/ytterbium doping concentration levels. The human eye is most sensitive to the green emission. This provides a ready visible indication of the length or region of the erbium glass gain element with sufficient pump absorption to reach greater than 50% population inversion.

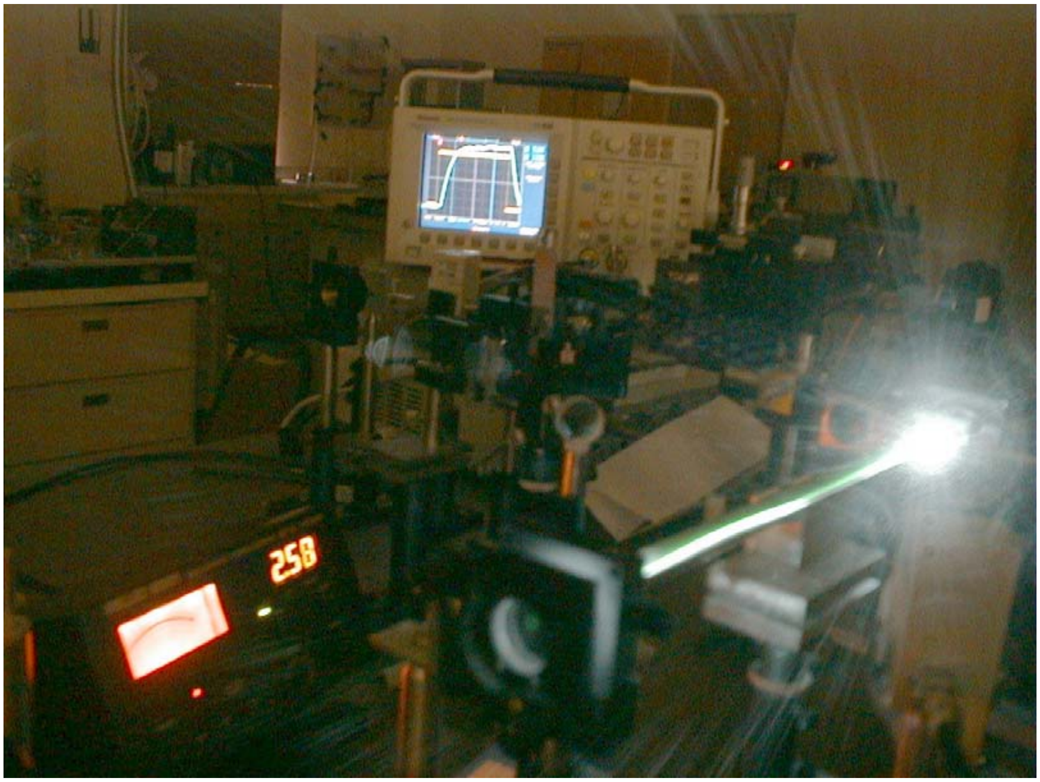

Fig. 3 DC LMA Er:Yb:glass fiber laser laboratory setup

The fiber laser threshold is about 250-300 mw of 975 nm pumping. The laser threshold is not significantly influenced by laser resonator optics. Fiber samples with multi-layer dielectric end-face coatings provided the highest slope efficiency values (37.6% see figure 4). These coatings consisted of the one face with 95% transmission at 975 nm and HR for 1535 nm and the second face 95% transmission at 1535 nm and HR at 975 nm. Data shown for un-coated fiber was produced with fiber samples of the same length. The fiber samples with the second highest output correspond to coated mirrors positioned very close to the fiber end-faces. With external resonator mirrors the 1.535nm laser output is about 88% of the coated fiber sample. The sample producing the lowest output corresponds to a pure ASE output (Fresnel reflection only) without the benefit of laser or pump cavity reflector optics.

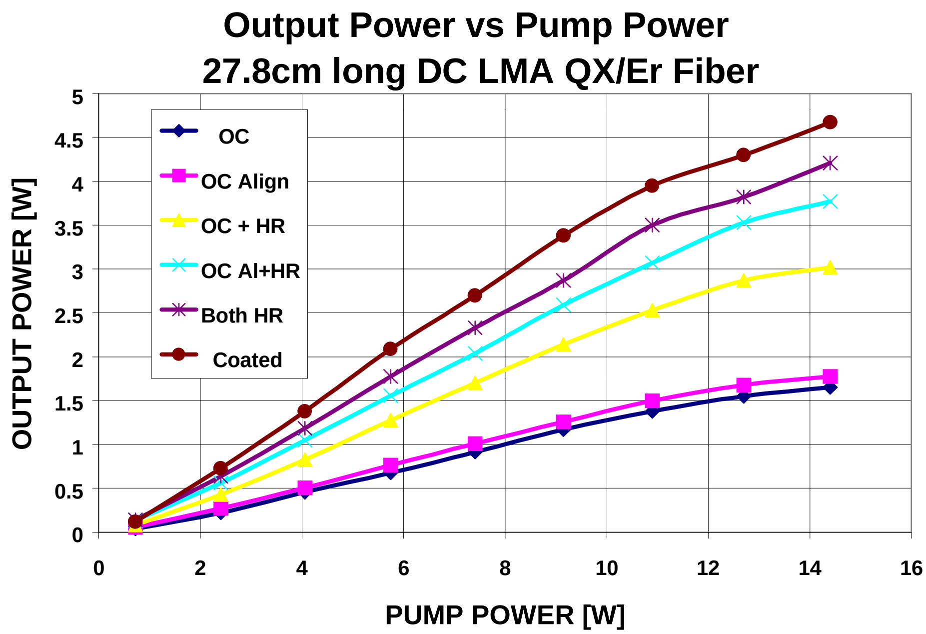

Fig. 4 Optical Efficiency Curve for QX/Er DC LMA Fiber

Figure 5 shows the typical output spectra of fiber laser at 4 Amp pump current level. The spectra displays 7 to 8 individual lines spaced a few nm apart. We suspect that these lines correspond to different longitudinal fiber LP modes.

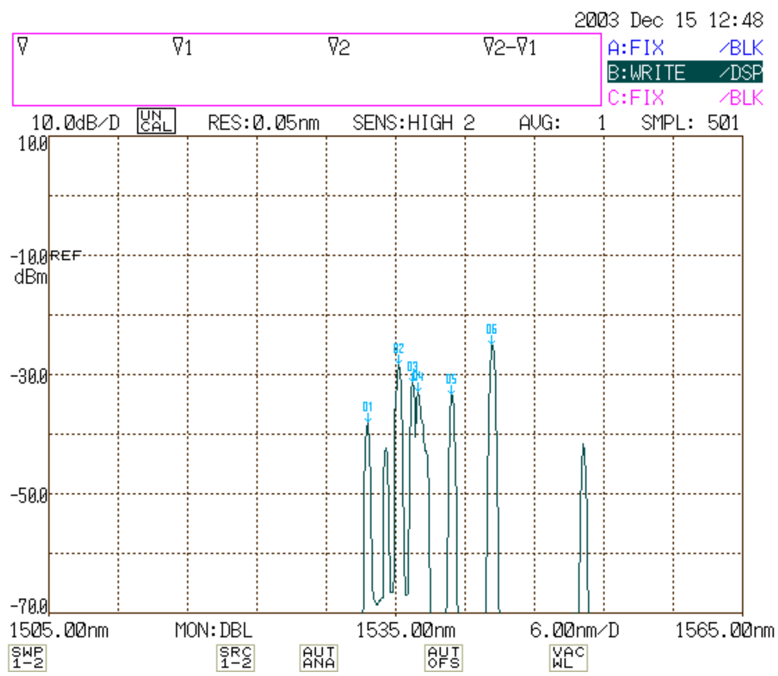

Fig. 5 Diode Array Output spectra @ 4-Amps Pump Current

Ytterbium Fiber Experiments

The ytterbium only DC LMA fiber sample has a 400µm x 400µm cladding with 25µm core. We tried to obtain an accurate measure of the background losses at the fiber absorption and laser wavelengths. The main problem is that the ytterbium's fluorescence emission peak is at nearly the same wavelength as the diode pump. This makes it difficult separate the pump and determine exactly how much ytterbium ASE output is produced. Figure 6 shows the output of a QX/Yb DC LMA fiber laser with different resonator output coupler values. Ytterbium exhibits lower gain when compared to erbium. Under similar pumping and resonator conditions the ytterbium fiber laser is less likely to produce ASE and more likely to produce a strong coherent output that is influenced by laser resonator optics.

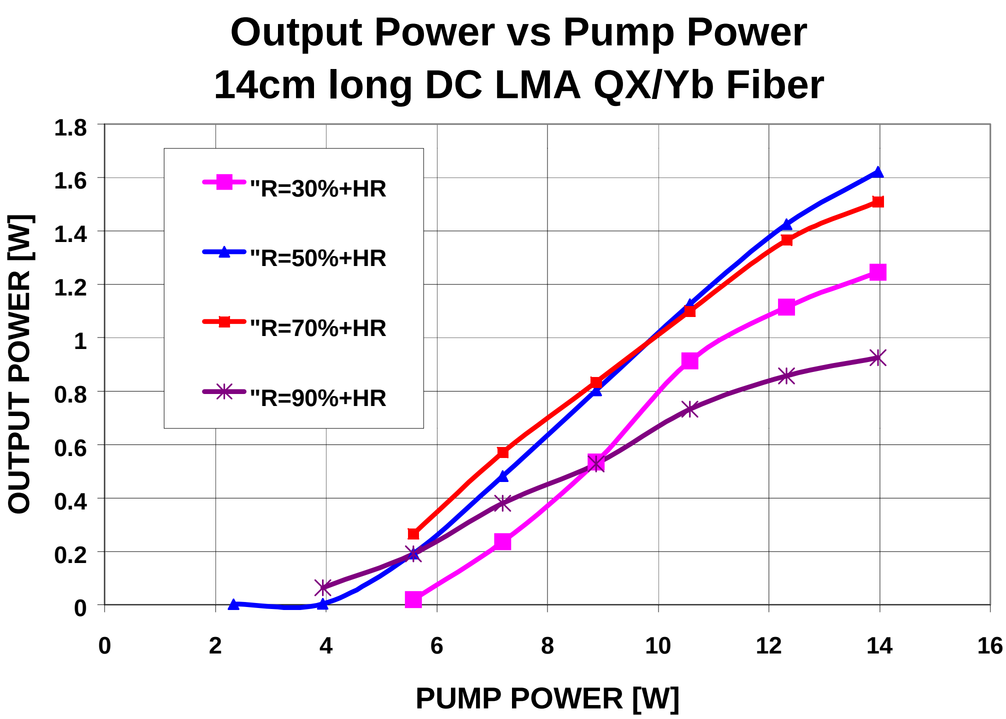

Fig. 6 Output Curve for QX/Yb DC LMA Fiber

With a 14 cm long QX/Yb ytterbium only doped fiber we obtained at maximum of 1.6 Watts CW output at 1061nm. The laser output wavelength is shifted towards the infrared from the Yb:phosphate glass peak at 1032nm. This shift is due to excessive scatter, defect, self-absorption and background losses in the fiber sample [7]. Under proper pumping conditions, a similar laser output wavelength shift has also been observed in erbium/ytterbium co-doped amplifier fiber [8]. When pumping the ytterbium fiber we observed a strong blue emission that appears to be up-conversion. The unexplained excited Ytterbium emission may be due to the presence of Yb^{2+} ions or impurities such as other rare earth contaminants.

Conclusion

We have demonstrated 4.67 Watts CW laser output power from a 27.8cm long CD LMA erbium/ytterbium doped phosphate glass fiber with a 37% slope efficiency and a 36.3% optical efficiency at 1535nm. The output appears to be LP_{11} spatail mode. We also demonstrated 1.6 Watts CW laser output power from a 14 cm long ytterbium only doped Phosphate glass fiber at 1060nm.

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