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High Gain Short Length Phosphate Glass Erbium- Doped Fiber Amplifier Material

Michael R. Lange, Ed Bryant
Harris Corp.
Government Communications Systems Division
P.O. Box 37 (MS: 13-9116)
Melbourne, FL 32902

Michael J. Myers, John D. Myers, Ruikun Wu, Christopher R. Hardy
Kigre, Inc.,
100 Marshland Road, Hilton Head, SC 29926
Ph# 843-681-5800, Fax# 843-681-4559, e-mail: kigre@aol.com

Abstract

A net gain per length of at least 1.1dB/cm has been demonstrated from a 4cm long section of non-optimized experimental fiber manufactured from Kigre's "MM-2" Er^{+3}-Yb^{+3}: phosphate laser glass. Laser oscillation has been demonstrated in the same fiber [1]. As much as 15.5dB of gain was produced previously from experimental erbium doped glass fiber, of otherwise similar composition, with a 5.1cm length [2]. Images of the 1538 nm mode field containment for the 4 cm MM-2 sample fiber indicate a good overlap match to standard communications transmission fiber, with fiber coupling loss measured at ~0.2 dB at 1318 nm.

Introduction

In the telecommunications field there is an ever-increasing demand for higher levels of integration and for smaller fiber-optic equipment and components [3]. One of the disadvantages of current standard EDFA's (*Fused Silica Based*) is their relatively limited capacity for producing large gain per unit length.. This leads to gain devices composed of individually fiber pigtailed components typically employing long fiber lengths (10 to 50 meters) requiring fiber wraps with bend radii of >30 mm. This produces amplifier architectures that are difficult to miniaturize, and incompatible with trends towards: automated assembly of small form factor modules, multi-channel devices, and integrated hybrid optics.

To date, development efforts in the communications industry have been, for the most part, focused on silicate and fluoride based materials for fiber optical amplification gain. The use of these materials has provided good performance, and allowed the growth of the long haul backbone in the telecommunications industry.

Extension of this technology down to the shorter metropolitan network level, has been slowed by the lack of need for gain, particularly at high component costs. As the networks evolve to more optical layer switching and cross connection the need for optical gain becomes more significant. In this arena, however, cost, compact size, and compatibility with small form factor, multi-channel modules become more important to address high-density complex optical architectures. "For *optical* amplifiers to become widely used, both the cost and the size must be reduced. Ideally, as in the electronics industry, all components would be integrated on a common platform such as a planar integrated optic *amplifier* wave-guide to reduce the cost of manufacturing". [4] "Unlike long-haul fiber optic links, emerging metropolitan networks rarely have long fiber runs that require conventional EDFA's, but their relatively complex architectures require several cascaded optical components to branch, route and switch light circuits. To overcome the losses caused by these components, a high gain, lower cost *optical amplifier component* is frequently required". [5]

Both integrated optic channel wave-guides and fibers with high gain per length coefficients can enhance the development of compact hybrid photonic modules. The particular focus of this work is on the investigation of fibers pulled from high gain per length coefficient phosphate glass. Both classes of devices are, however, readily fabricated from the same material, as discussed below

Phosphate laser glass is an attractive amplifier material because unlike fluoride and silicate materials it combines all of the required properties of good chemical durability, ion-exchangeability, high gain per length coefficient, wide bandwidth capability, and low up-conversion characteristics [2]. Phosphate glass also exhibits a high solubility for rare earth ions. This allows large concentrations of active ion to be introduced into a relatively small volume. The high ion density results in a significantly smaller optical gain device than can be fabricated out of silica based glasses traditionally used for fibers.

Erbium-ytterbium doped phosphate glass technology, in particular, has demonstrated a significant capacity for large gain per length coefficients [6,7,8], in addition to the providing the ability to tailor the absorption by the ytterbium concentration. Furthermore, various experimental devices have been demonstrated for fiber-optic transmission applications supporting data rate capabilities in the multi-Gb/sec range.[9,10,11,12]. These combined aspects of the phosphate glass material and reported results support it as a prime candidate for producing compact photonic modules employing gain.

A comparison of representative optical gain per length coefficient measurements for erbium in various glass base materials is shown in Table 1. This table illustrates the orders of magnitude of gain per length coefficient typically obtained in the various glass bases.

Table 1. Representative Erbium doped gain measurements comparisons in various glass base materials, for pumping at 980nm and 1480nm, made by [2]U of Arizona, [12]NTT Photonics Laboratories, [13]British Telecom and [14]Lucent. [2,12,13,14]

980nm pump		**1480nm pump**	
Silica[4]	**MM-2**[2]*	**Telurite**[13]	**Flouride**[14]
2.5dB/meter	3dB/cm	2dB/meter	0.13dB/cm

MM-2 Fiber Characterization

One of the obvious advantages of fiber based devices, over channel waveguides, is the ease of achieving a better mode match to transmission fibers, in addition to polarization insensitivity. Figure 1 shows a comparison of modes fields observed in a fiber sample of erbium core doped phosphate glass, and that of standard transmission fiber corning SMF-28™

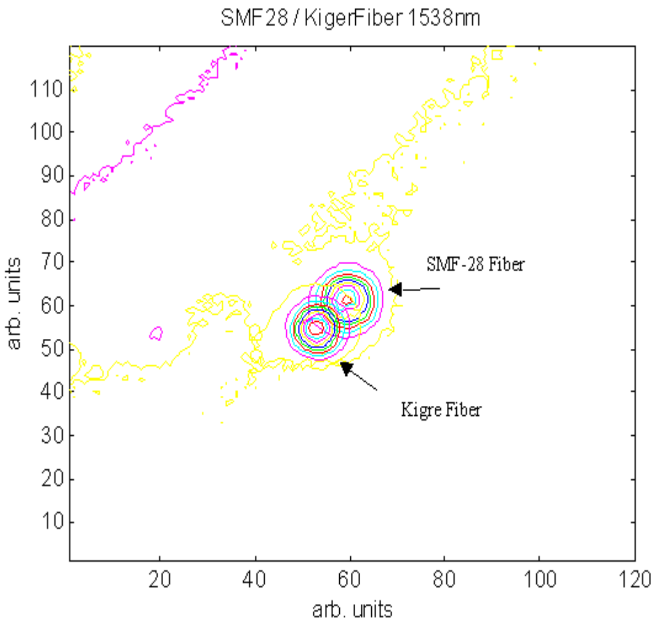

Figure 1. MM-2 phosphate glass fiber mode field images captured at the exit plane of the respective fiber, compared to a standard matched clad fiber.

The images indicate a good 1.54µm mode match to standard communications carrier fiber. The MM-2 based fiber was fabricated with a delta n of 0.01 and an erbium ytterbium fiber core of 8 microns. The cladding was constructed of an un-doped phosphate glass, of otherwise similar chemical composition. This glass was pulled to be similar to standard matched clad fiber for laboratory comparison, and not specifically designed to optimize mode confinement for maximum gain coefficient (dB/mW).

The total throughput loss was measured to be 1.6 dB at 1318 nm. The combined input and out put coupling loss assessed to be 0.4 dB using an estimated 0.3 dB/cm loss (scaled from Spectrophotometry data) at 1318 nm. This is reasonable in comparison to the 1 dB determined on the erbium fiber sample with a 5 micron core [2], due to the better mode overlap match for the 8 micron MM-2 sample.

Preliminary gain measurements on the MM2 phosphate glass fiber, when pumped co- and counter propagating at 975 nm and 978 nm are shown in Figure.2, compared to results obtained on a channel wave-guide fabricated from the same MM2 recipe.

The fiber results are quite promising. As discussed previously, the core was not designed for high mode field confinement, to optimize the gain coefficient, but instead, to optimize mode coupling to a standard telecom fiber. Also, the lower pump powers used on the fiber, compared to the channel wave-guide, was a result of pump laser problems. Pump saturation has clearly not occurred, and further characterization will be performed when the pump lasers are replaced.

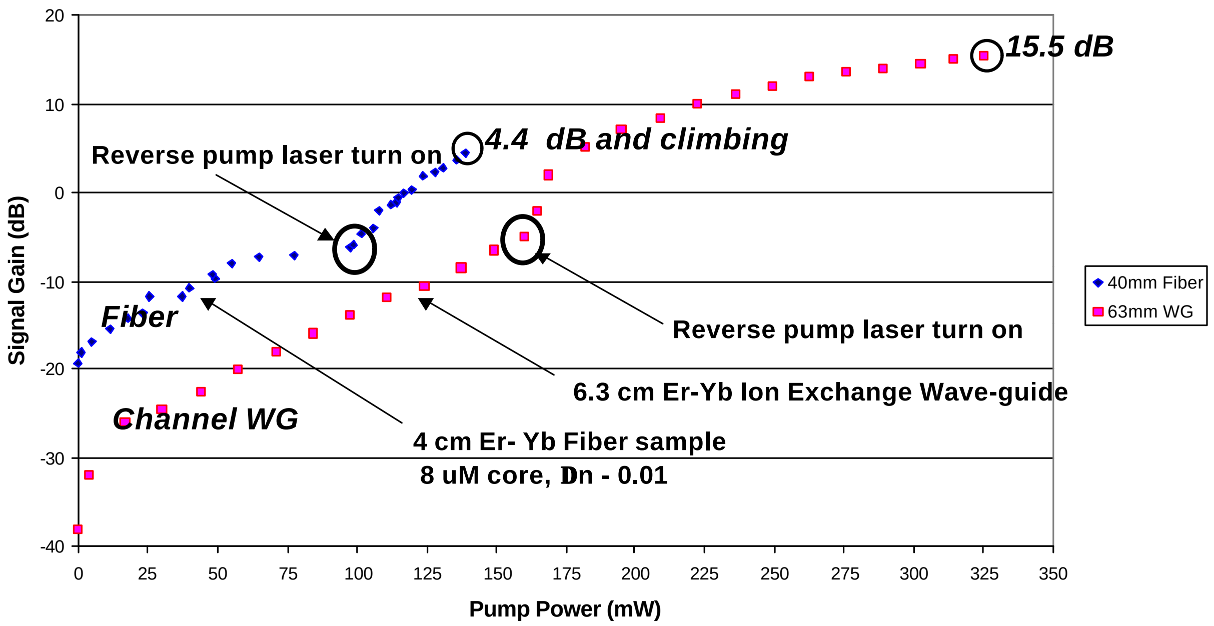

Figure 2. Net Gain Vs pump power for the MM-2 fiber, compared to results obtained on a channel wave-guide of the same MM-2 mixture

Material Characterization

A more thorough evaluation of the phosphate glass fiber fabricated from the mixture referred to as MM-2 is underway. Some basic testing was performed prior to the fiber pull in order to understand some of MM-2's characteristics, and to help characterize the recipe. Spectrophotometer scans were performed to characterize the spectral absorption across the pump and signal regions, and gain characteristics were measured.

The spectrophotometer scan was performed on bulk samples of the material, comparing samples with no ytterbium (only erbium) to that of equal wt % of Er-Yb. The gain characteristics were measured by fabrication of a single mode channel wave-guide in the substrate material

The spectrophotometer scan shown in Figure 3, illustrates transmission across the entire pump and signal bands to emphasis the effect of Yb. A detailed view of the pump and signal regions in terms of attenuation provides insight to support analysis efforts.

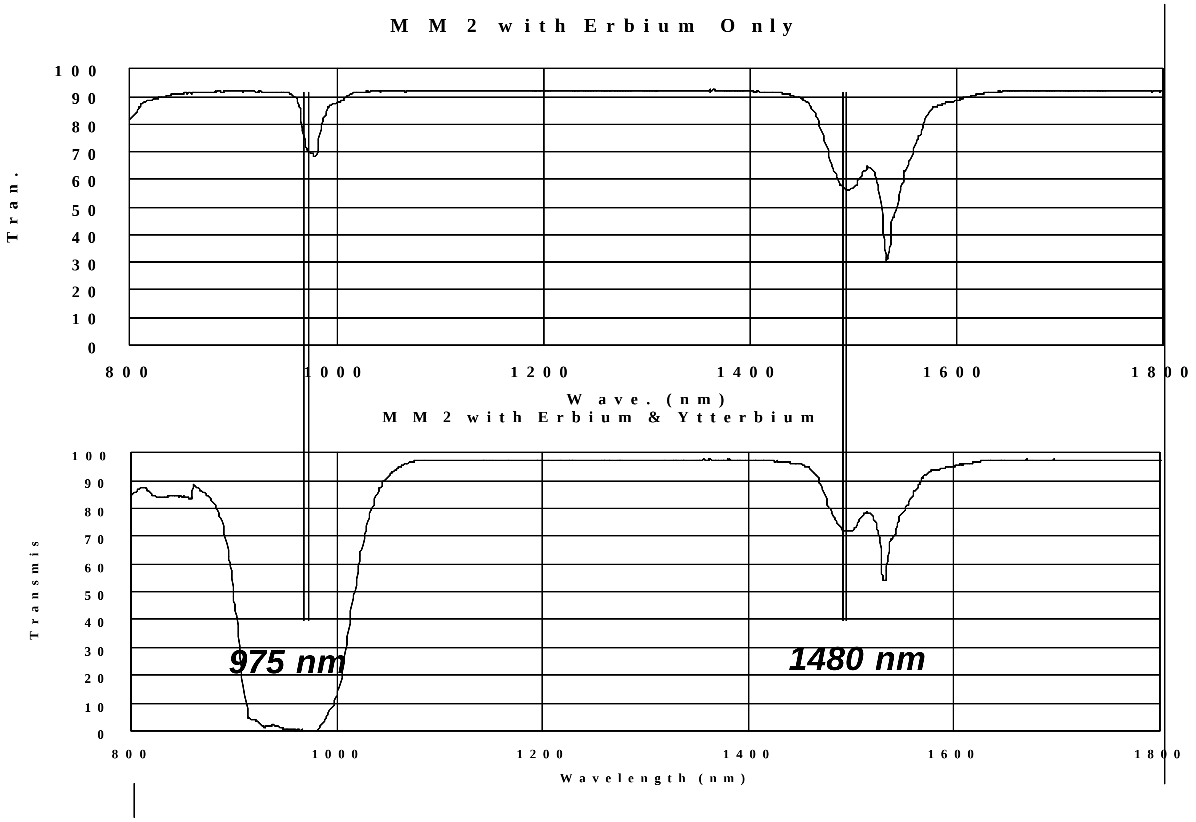

Figure 3. Spectral Transmission scan of MM-2 Er, and MM2 Er-Yb Phosphate glass mixture used for the active fiber core in the fibers and the channel wave-guides

One difficulty, however, in analyzing and understanding the impact of the Yb is in developing an understanding of subtleties of the energy transfer interaction of erbium and ytterbium. While the energy transfer properties between ytterbium and erbium are well known, subtleties in the dynamics are not well understood, and anomalies in behavior are observed. Though theoretical models have been presented [15], as in any highly nonlinear multivariable phenomena, numerical analysis can be challenging, particularly when quantification of all the basic parameters is not clear.

Given the challenges of a good quantitative analytic understanding of the ytterbium erbium interaction, the experimental work performed to assist in the analysis can also assist in providing an empirical understanding. Signal gain measurements were performed in channel wave-guides under various conditions. The channel wave-guides were formed using an ion exchange salt bath with silver as the high polarizability ion. Mode fields were then measured to assure good modal characteristics.

The mode fields shown in Figure 4 correspond to a measured 1 dB fiber to fiber coupling (0.5 dB per facet) at 1318 nm.

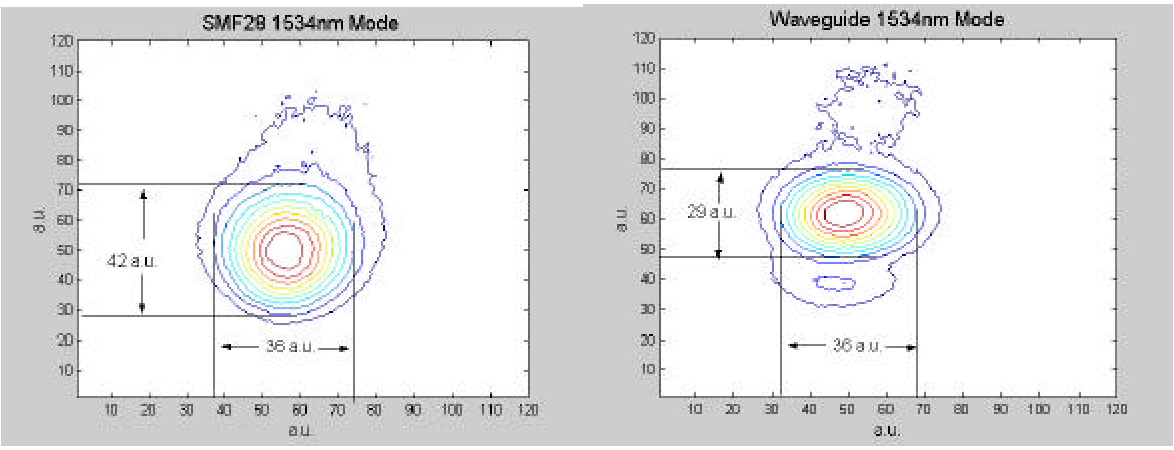

Figure 4. MM-2 phosphate glass channel wave-guide mode field images captured at the exit plane, compared to a standard matched clad fiber

Figure 5 illustrates the net fiber to fiber gain achieved in a channel wave-guide under conditions of co- and counter propagating pumps. The curve illustrates the process of pumping a 63 mm wave-guide with one pump laser on up to about 160 mW, then initiating the second pump to a total of 325 mW. In the top curve the reverse pump was initiated first. The obvious change in slope beyond 160 mW is likely due to the reverse direction pump accessing the far end erbium ions deficient in excited states, (i.e., low fractional population inversion). This assessment is supported by analysis. This would tend to imply that the 2.5% wt. level of ytterbium concentration might be too high for the 63 mm length, in channel wave-guide form. The analysis also indicates that the result would improve for a fiber pulled from the same material due to the Er-Yb ion concentration being centered in the higher intensity core regions of the guided mode. This will be verified when new experiments are constructed with longer fiber samples.

One further test was performed on the fiber sample to verify activity due to pumping at 1480 nm. Figure 6. was provided by Photon-X (an independent communications R&D laboratory). Researchers indicate 10-26dB of signal enhancement in an 8.8cm length of fiber with 300mW of 1480nm pump and a tunable signal source of 1520-1580nm. Although the activity is clear, the signal enhancement (gain effect) is less than expected. Optimization of the phosphate-based material has many similarities to its silica based erbium doped cousin, however, the impact of high-density erbium and ytterbium is not fully understood. The optimization is, therefore, not assumed to be directly scalable from well-known erbium doped silica results.

Conclusion

High dopant concentration phosphate laser glass fiber offers the potential for high gain per length coefficients, allowing the construction of compact devices compatible with trends towards: automated assembly of small form factor modules, multi-channel devices, and integrated hybrid optics. Phosphate glass includes advantages of a high solubility for rare earth ions (allowing the high dopants), chemical durability, ion-exchangeability, wide bandwidth capability, and low up-conversion characteristics.

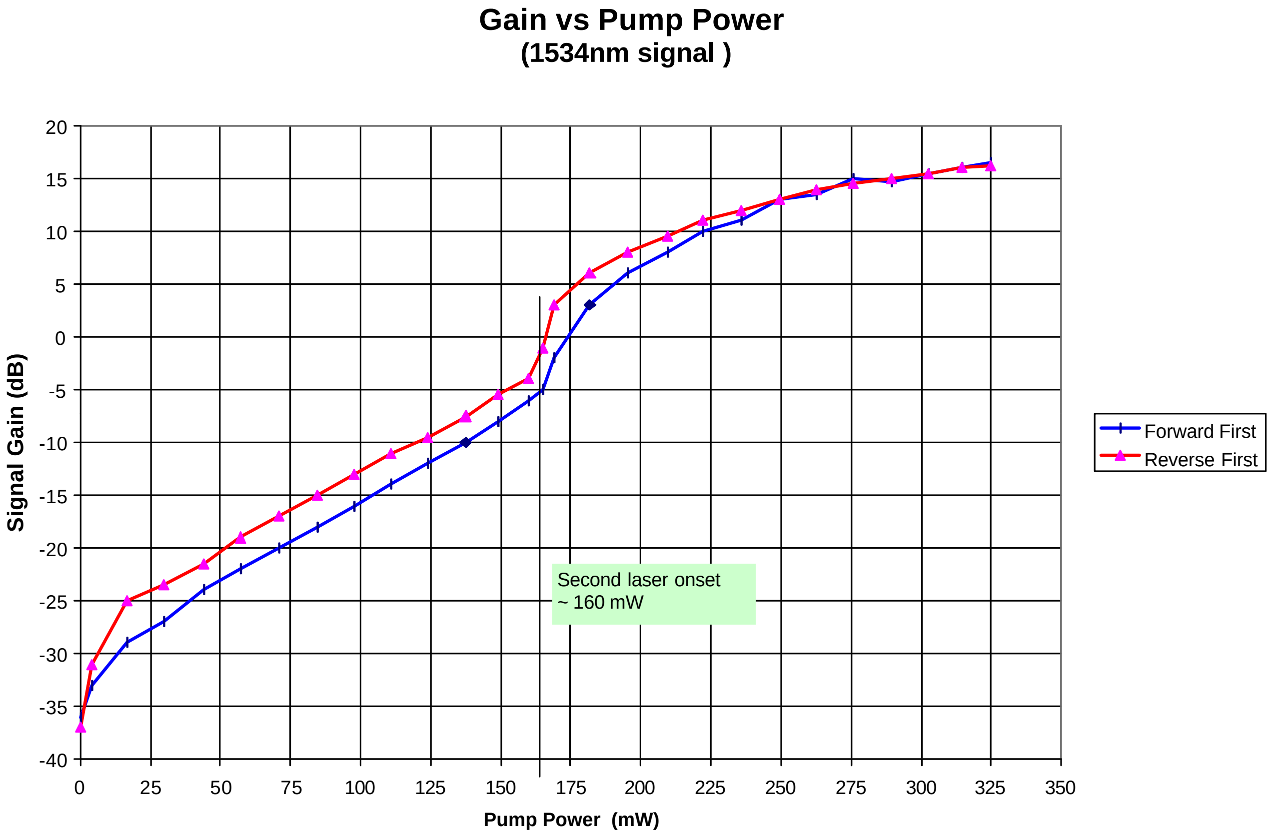

Figure 5. Net gain measurements taken on a 65 mm sample of MM-2 with an ion exchange channel waveguide

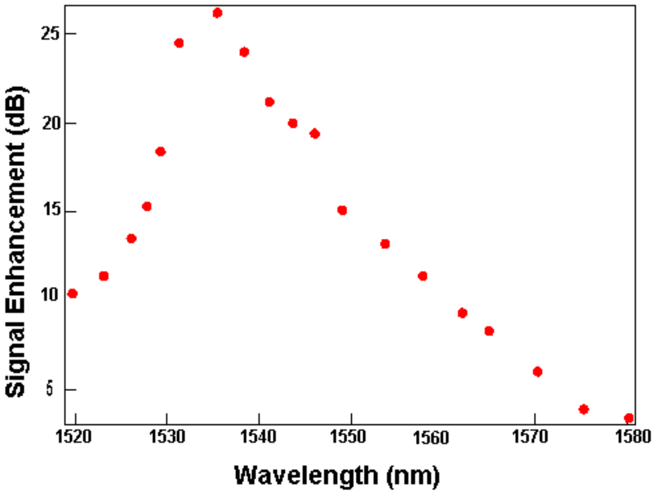

Figure 6. Signal Enhancement Measured Across 1550 +/- 30 nm for Pumping at 1480 nm

Ytterbium doping provides versatility in pump optimization for a given gain length. The broad absorption allows an expanded choice of pump wavelengths, although the interactions are not fully understood. Fibers fabricated from this material are observed to be low loss and of high quality for the gain lengths involved and thus, merit further study.

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