High Gain Coefficient Phosphate Glass Fiber Amplifier

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Abstract

High gain density materials offer the potential of compact configurations amenable to integration of gain into telecom modules, which are increasingly becoming high packing density configurations. Such modules may function as ‘loss-less’ splitters, wavelength filters and demux’s, dispersion compensators, switches, add-drop nodes, and the like. These components are becoming much more prevalent in fiber based communication systems as data rates increase and switching and routing moves more into the optical layer. To this end, phosphate glass material, with its high solubility for rare earth ions, is an attractive host candidate. The focus of this particular work is to explore the physical and dimensional parametrics associated with rare earth doped phosphate glass host material for the purpose of determining its benefits, limitations, and suitability as a compact gain media, and understanding its design trade space for design optimization. Within this domain, core design parameters including index delta, core diameter, pump parameters, coupling interface, and rare earth doping densities, are the dominant parametrics of interest.

Introduction

In the telecommunications field there is an ever-increasing demand for higher levels of integration and for smaller, higher channel density fiber-optic equipment and components. As the networks evolve to more optical layer switching, filtering and cross connection the need for optical gain distributed throughout the network becomes more significant. In this arena, however, cost, compact size, and compatibility with small form factor, ribbonized multi-channel modules become more important to address high-density complex optical architectures.

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.

Phosphate laser glass is an attractive amplifier material because it combines the required properties of good chemical durability, high gain density, wide bandwidth emission spectrum of erbium, and low up-conversion characteristics [1]. Phosphate glass exhibits a high gain density due to a high solubility for rare earth ions. This allows large concentrations of active ions 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 doped silica fiber is typically characterized by gain coefficients on the order of 2 to 3 dB/meter, whereas erbium phosphate glass is on the order of 2 to 3 dB/cm.

Erbium-ytterbium doped phosphate glass technology, in particular, has demonstrated a significant capacity for large gain per length coefficients in addition to providing the ability to tailor the absorption by the ytterbium concentration. These combined aspects of the phosphate glass material, and reported results, support it as a prime candidate for producing compact photonic modules employing gain.

One challenge of phosphate glass as a high performance integrated gain media is that its properties are quite different from the silica based fiber it must interface to. That makes glass fusion splicing, core tapering, and general mode impedance matching more difficult than silica based amplifiers. The gain optimization is also different than silica based erbium fibers, so some new rules have to be learned. As such, laboratory experimental results and analysis that have impact on the design and optimization of phosphate glass fiber for amplification are of interest.

Previous Experiments

An experimental wave-guide manufactured from Kigre's "MM-2" Er^{+3}-Yb^{+3} doped phosphate laser glass demonstrated 15.5dB of gain, in previous work [2], and larger gain has been achieved by others [3,4]. The wave-guide was a silver ion-exchange device in an erbium ytterbium doped glass substrate. The device was a 6.5 cm sample producing a net 2.3 dB/cm peak gain coefficient at 325 mW of combined pump power in a co- and counter-propagating configuration. At the same time preliminary work presented showed promising results of new fiber samples pulled with a core of the same material. Similarly others [5] have presented results from a 5.1 cm segment of fiber pulled from a similar doped phosphate glass mixture that achieved 15.5 dB of gain, and more recently 21 dB in 7.1 cm of fiber length [6].

Analysis performed suggests that a fiber offers more performance potential than an ion exchange wave-guide for a number of reasons. 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 mode fields observed in a fiber sample of erbium core doped phosphate glass, and that of standard transmission fiber, Corning SMF-28^{TM}. The images of the 1.54 um mode field containment for the MM-2 sample fiber indicate a good overlap match to standard communications transmission fiber with fiber coupling loss measured at <0.3 dB at 1318 nm. The MM-2 based fiber was fabricated with a delta n of 0.01 and an erbium ytterbium fiber core of about 7 microns. The cladding was constructed of an un-doped phosphate glass of otherwise similar chemical composition.

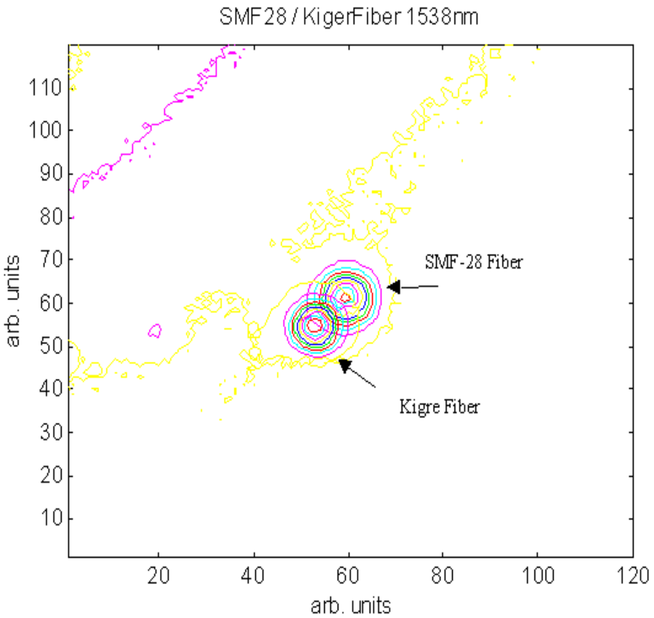

Figure 1. MM-2 phosphate glass fiber mode field images captured at the exit plane of the respective fiber compared to a standard matched clad fiber.

Another significant advantage of fiber over a traditional ion implanted wave-guide is the fact that the Er^{+3}- Yb^{+3} is doped throughout the substrate in which the wave-guides are implanted. This is due to fabrication technique. It is very complex to fabricate a doped wave-guide within an un-doped substrate. The full optical mode field experiences the Er^{+3}-Yb^{+3}doping, whereas maximum inversion exists dominantly within the central high intensity pump field region. As such, both the pump and the signal fields suffer excess attenuation in the evanescent field that contributes little to gain. The ability to confine the active gain to the central higher intensity regions of the optical field, and optimization of the field confinement, has been exploited for years in silica fiber amplifiers.

One disadvantage of utilizing phosphate glass, as opposed to silica glass, is the extreme difference in its physical properties from silica transport fiber. Silica based amplifiers can be readily fused with fusion recipes that allow transition of the mode field down from its typical 10 micron diameter confinement core in the transport fiber to on the order of 5 micron diameter in the optimized amplifier fiber. This can be done in a nearly ‘adiabatic’ manner that minimizes radiation loss in the mode transition. Similar techniques are not readily available when fusing silica fiber to phosphate glass fiber. The difference in softening temperatures alone of approximately 1000 ^{o}C makes this quite difficult.

Experiments

Successful fusion between phosphate and silica glasses has, however, been demonstrated. **Figure 2**. illustrates a fused sample fabricated in our lab that demonstrated low insertion loss (< 0.5 dB), and was shown to be mechanically durable. This particular sample had a 180-micron cladding diameter. The larger diameter was shown to be beneficial in that the additional thermal mass of the phosphate glass added thermal capacity to help balance the disparity in softening temperatures during fusion. While successful fusion results were demonstrated, repeatability of the results was poor. The MM2 core had a diameter of about 8 microns for mode matching considerations. Tapering between significantly different core diameters is even more challenging. Experimentally measured net gain of 28 dB was achieved in a 12 cm long sample fused to silica fiber using 365 mW of 976 nm pump power.

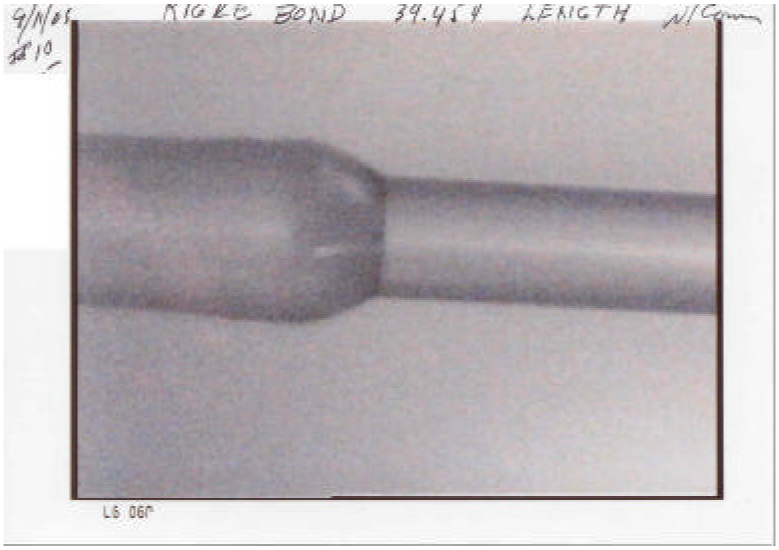

Figure 2. 180-micron diameter phosphate glass fused to SMF-28^{TM} silica glass fiber

A number of experimental 125-micron clad phosphate fibers were also fabricated. A simple butt-coupling configuration with an APC (angle polished) interface between standard matched clad SMF-28^{TM} and MM2 phosphate glass amplifier fiber was used for experimental characterization. It is in these devices that the most repeatable results were obtained, and thus, the majority of experimental characterization was conducted with the APC butt coupling approach.

Results and Analysis

For simple butt coupling interfaces the mode diameter difference between the two glass fibers forms a trade between pumping efficiency and amplifier noise figure. The impact that mode mismatch has on the amplifier input insertion loss is particularly important since the impact on noise figure is essentially dB for dB. Higher pump photon intensity produces more effective maintenance of population inversion and lower gain thresholds. The trade, thus, consists of a balance between input signal insertion loss along with mode stability, and mode confinement for higher intensity. **Figure 3**. illustrates an analysis[7] of the dependence on core diameter of the signal wavelength mode fields for the two glass fiber types. Similar plots can be generated for the pump wavelengths for which multimode behavior can occur.

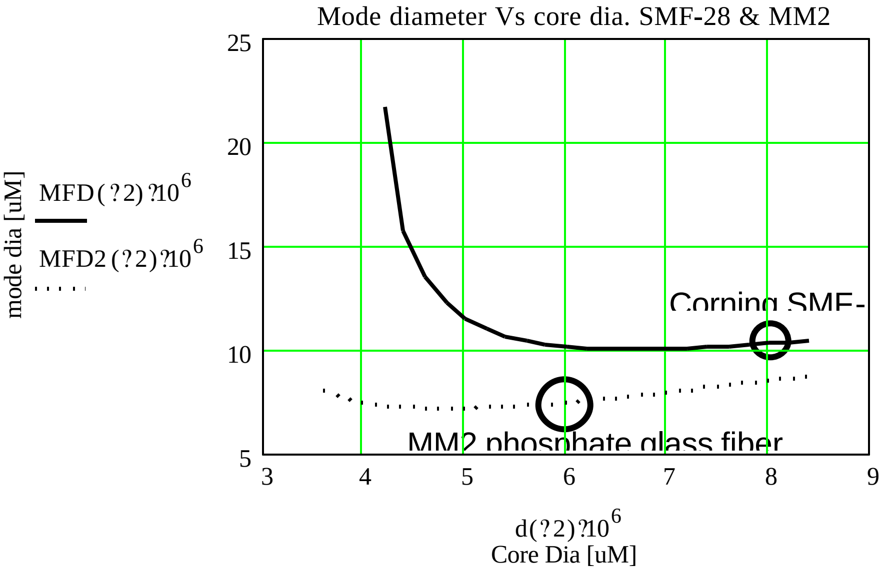

Figure 3. SMF^{TM}-28 and MM-2 phosphate glass fiber mode diameter as a function of core diameter

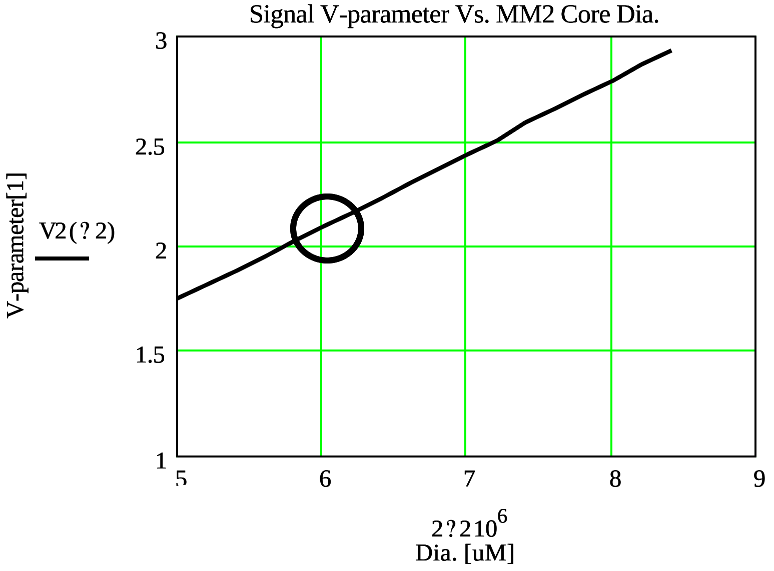

Figure 4. MM-2 phosphate glass fiber V-parameter as a function of core diameter

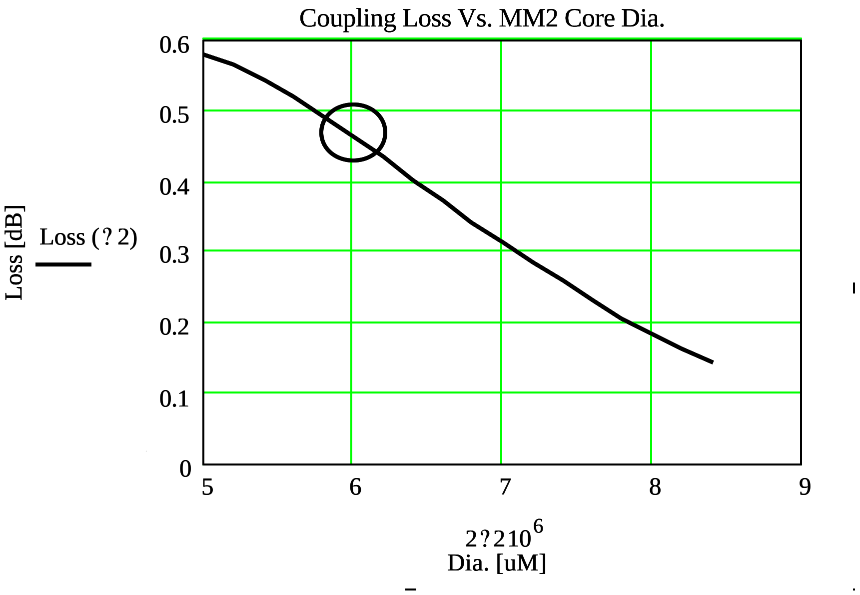

Figure 5. SMF-28^{TM} to MM-2 phosphate glass fiber coupling loss analysis calculated from mode overlap theory[7]

Mode mismatch losses necessitated by a butt-coupling configuration are desired to be < 0.5 dB at the signal wavelengths. This places a limitation on the minimum phosphate fiber core diameter at a given index delta. The amplifier V-parameter of the propagation is desired to be approximately the same value as the transport fiber SMF-28^{TM} (~ 2.1 at the signal wavelength) in order to help maintain stability of the mode through the abrupt interface transition. **Figure 4** illustrates the dependence of V-parameter on core diameter. **Figure 5** illustrates the dependence of mode transition loss on the core diameter of the MM2 phosphate glass.

Based on these various considerations the core index delta of the phosphate glass was selected to be 0.01 with a core diameter of 6 microns. Analysis of the coupling loss (shown in **Figure 5)** at these values indicates that the signal loss should be below 0.5 dB. Measurements of the coupling loss at 1318 nm, along with noise figure measurements at the signal wavelength, support that < 0.5 dB insertion loss was achieved.

The choice of Er^{+3} and Yb^{+3} concentrations forms a complex trade in itself. The doping composition was approximately 2-wt % of each rare earth oxide compound. This composition appears to provide a good balance of the desired gain per length, pump absorption over the broad Yb^{+3} absorption band, and the Yb^{+3} to Er^{+3} energy transfer rate (calculated to be > 90%)[8,9]. There is no specific claim that this is an optimum composition, however performance results, shown below, are quite promising. Gain measurements on the MM2 phosphate glass fiber, pumped co- and counter propagating at 976 nm, are shown in **Figure 6** and **Figure 7**. This sample had the core parameters of 0.01 ? n and an approximately 6-micron core diameter. Peak fiber-to-fiber gain of > 40 dB was achieved on multiple samples, producing ~ 2.8 dB/cm, at the combined pump power of approximately 350 mW.

Bi-directional pumping was used to optimize the population inversion along the full fiber length. The relatively high ytterbium absorption cross section and energy transfer rate, at the mode confinement in these samples, supported this approach. A higher level of mode confinement with a smaller core should enhance pumping efficiency somewhat, but would produce more insertion loss due to mode mismatch at the input, thus impacting noise figure. The noise figure measurements were < 4 dB at peak gain for the fiber samples. The noise figure result reflects the fiber gain material and the interface coupling to it. The measurement was referenced to the input pigtail connector that interfaced to the phosphate glass connector, down-stream from the WDM pump coupler. An amplifier product would include the loss contribution of the WDM coupler and possibly an isolator on the input leg.

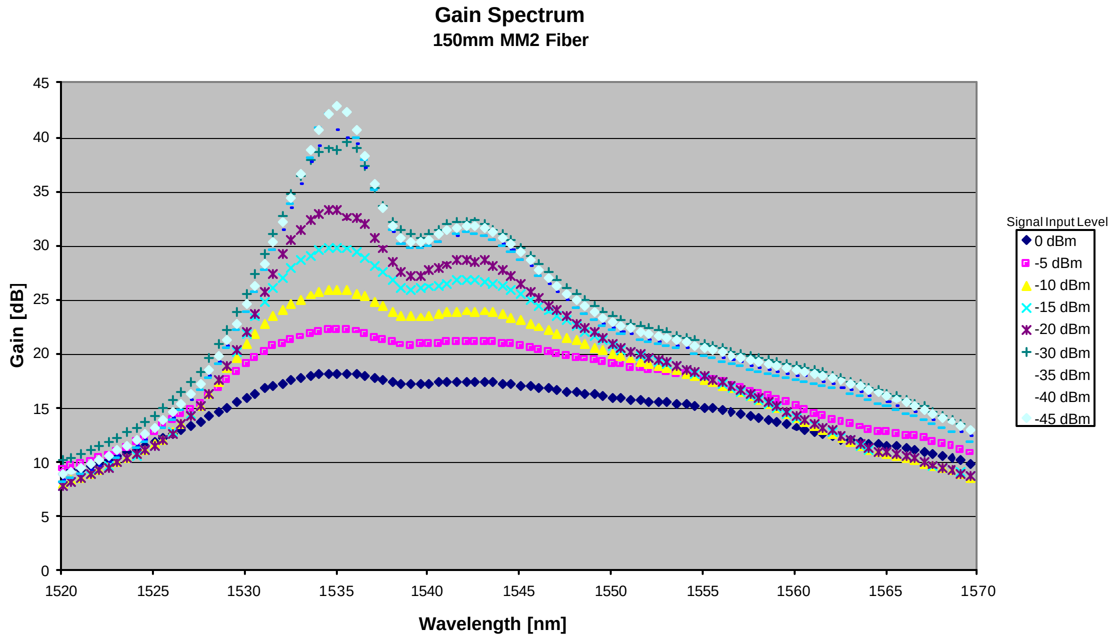

Figure 6. Net gain spectrum of signal inputs ranging from small signal to saturated

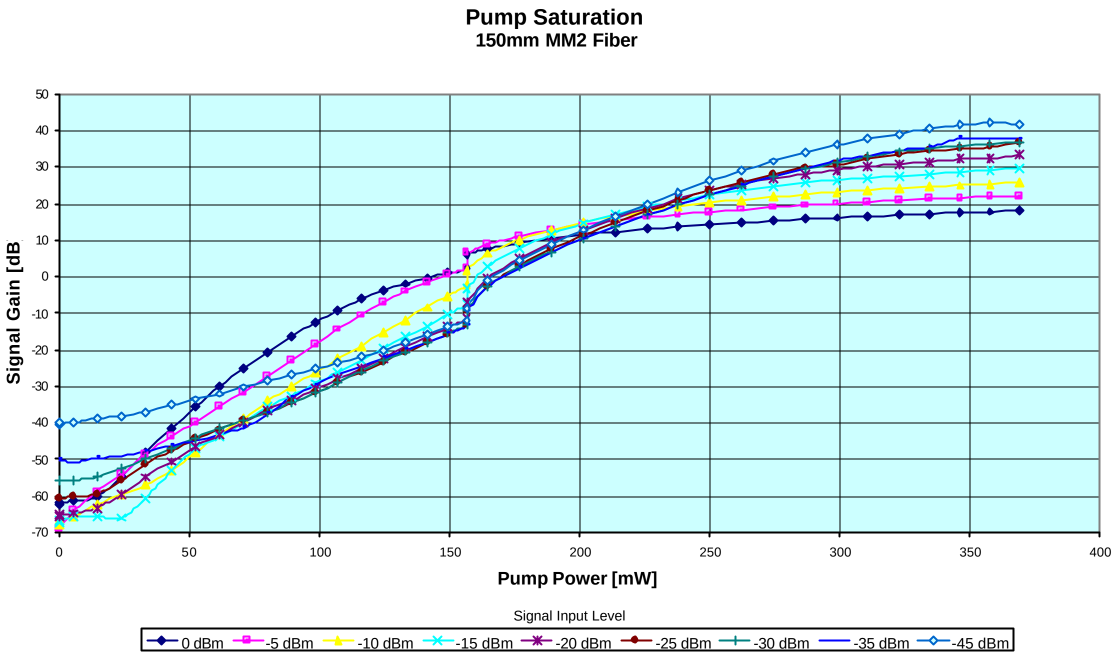

Figure 7. Signal gain Vs pump power with signal inputs ranging from small signal to saturated

Material Characterization

Spectrophotometer scans were performed to characterize the spectral absorption across the pump and signal regions. The spectrophotometer scan was performed on bulk samples of the material, comparing samples with no ytterbium (only erbium) to that of about equal wt % of Er^{+3}-Yb^{+3}. The spectrophotometer scan shown in **Figure 8** illustrates transmission across the entire pump and signal bands to emphasize the effect of Yb^{+3}. A detailed spectral scan of the pump and signal regions provides insight to help support analysis efforts.

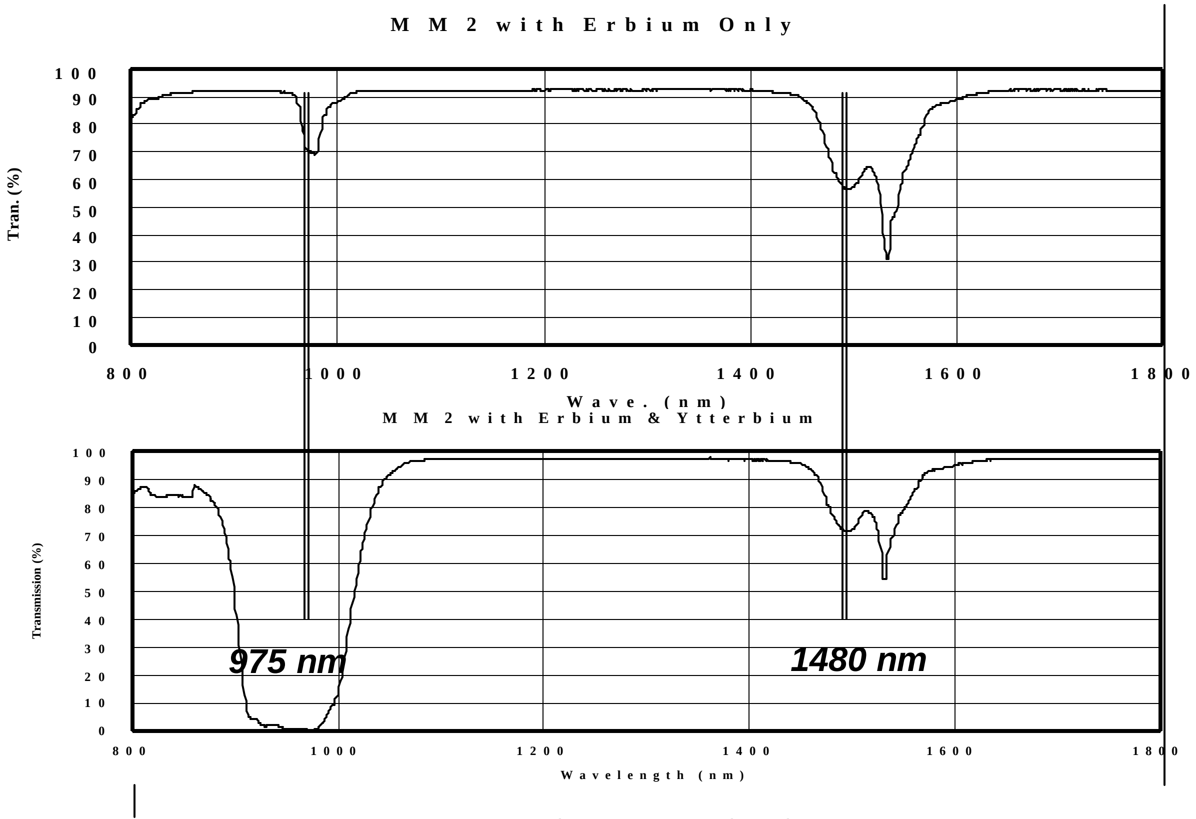

Figure 8. Spectral Transmission scan of MM-2 Er^{+3} and MM2 Er^{+3}-Yb^{+3} phosphate glass mixture used for the active fiber core in the fibers

Conclusion

While there is no claim that the results here represent a performance optimized amplifier, we firmly believe that the results support the claim that erbium doped phosphate glass is a viable candidate for a high gain per length material that may be amenable to integration into telecom modules, providing active gain. We believe that a useful gain profile has been demonstrated, and the results support that a butt coupling interface utilizing APC connectors is a viable implementation approach. Work will continue on trading and bounding the basic material parameters and constituents. In addition, preliminary results obtained with silica fiber fused to the phosphate glass indicate that further efforts towards optimization of the splicing process may be justified. Alternatively, mode field tapering in the silica fiber with a butt-coupling interface to a smaller diameter mode field in the phosphate glass may offer some benefit to pumping efficiency.

Acknowledgements

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