Multi-mode pumped amplifier using a newly developed 8-cm long phosphate glass fiber

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Abstract: A fiber amplifier with a net gain of 43dB at 1535nm and 21dB over the full C-band was demonstrated using a newly developed 8-cm long erbium-doped phosphate fiber excited with a 1 W 975nm multimode laser diode. A theoretical model was developed for multi-mode pumped amplifier using a very short fiber.

1. Introduction

Phosphate glass fibers allow doping with high Er^{3+} concentration without the deleterious effects of ion clustering, making possible erbium-doped fiber amplifiers using very short (a few cm) fiber lengths. In our previous work we demonstrated phosphate glass amplifiers with a high gain per unit length pumped with single mode 980nm diode laser [1,2]. However, the net gain over the C-band was limited to 5dB. In this paper we report a multi-mode pumped fiber amplifier using a newly developed phosphate glass fiber. A net gain of 43dB at 1535nm, 27dB at 1550nm, and 21dB over the C-band was achieved from an 8cm-long fiber excited with a 1W, 975nm broad area multi-mode laser diode. To the best of our knowledge, this is the highest gain per unit length reported for fiber amplifiers. Importantly, the gain is comparable to typical silica fiber amplifiers containing several meters of fiber.

These results were obtained by pumping with broad area multi-mode laser diodes, which deliver a dramatic cost reduction as compared to single mode pumped amplifiers. Further cost reduction can be realized by forming extremely compact fiber amplifier arrays with short fibers on silicon or glass substrates which share the multi-mode pump laser. A theoretical model indicates that our specially designed active fibers can efficiently absorb the multi-mode pump laser in the fiber's inner cladding in only a few centimeters length while typical silica fibers need a few meters to absorb the multi-mode pump laser.

2. Glasses and Fibers

New core and cladding glasses containing a high concentration of Al_2O_3 were designed to ensure high mechanical strength and good chemical durability. The mechanical strength and the chemical durability were further enhanced by eliminating the alkali ions (K^+, Na^+, Li^+), which are contained in most commercial phosphate glasses. Therefore, fusion splicing between the phosphate glass fiber and the silica fiber can be reliably achieved as illustrated in Figure 1. The cladding glass composition was designed to match the thermal properties of the core glass to ensure low stress in the fiber. Er^{3+} and Yb^{3+} doping concentrations were selected based upon theoretical modeling and spectral characterization results, especially considering the cooperative up-conversion. Er^{3+}/Yb^{3+}-doped phosphate glasses and un-doped cladding glasses were melted at 1350°C in a platinum crucible using high purity starting chemicals. The refractive indices of the glass samples were measured with a prism coupler at 632.8nm, 1300nm and 1550nm. The absorption and emission cross-sections were determined to be $0.75\times10^{-20}cm^2$ and $0.82\times10^{-20}cm^2$ at 1534nm, respectively. The glass transition temperature and softening temperature of the core glass were

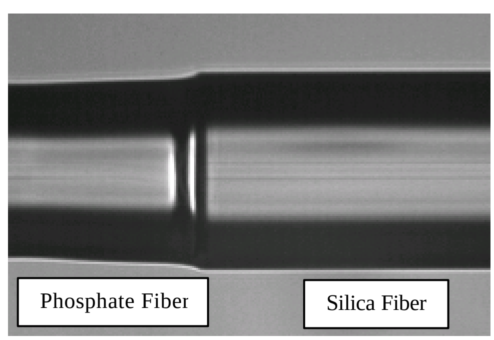

Figure 1. Fusion spliced joint between phosphate and silica fibers

measured to be 583°C and 620°C, respectively.

Single mode double cladding phosphate glass fibers were fabricated using a rod-in-tube technique. The fiber drawing temperature was 765 °C and no plastic coating was applied to the fiber. The numerical apertures of the core and the cladding were calculated to be 0.145 and 0.24 at 1550nm, respectively. Fibers with core diameters of 6μm, 6.6μm, and 7μm were fabricated, each with Er^{3+} ion concentration of 3-weight% and codoped with Yb^{3+} to provide a high absorption coefficient for the pump.

3. Amplifier characterization and theoretical simulation

Amplifier performance was evaluated experimentally using fibers with 6.6μm core diameter and various lengths between 6cm to 9cm in a double-pass configuration excited with a Spectra-Physics 975 nm broad area laser diode. This paper mainly reports the results obtained from the 8 cm-long fibers. In this experiment a three-port circulator was used for input and output of signal light, and a dielectric coating on a fiber face was deposited to reflect both the signal and the pump. A proprietary coupling device was used to efficiently couple the single-mode signal and the multi-mode pump into the doped fiber structure. The phosphate glass fibers in the amplifier were fusion spliced to silica fibers.

Figure 2 illustrates the measured and simulated gain spectra at different signal input powers for the 8cm-long fiber excited with a 1W broad area laser diode. A peak gain of 43dB and 41dB was achieved at 1535 nm with –35dBm and –30dBm input signal, respectively, which represents a gain per unit length of greater than 5dB/cm. A low cooperative up-conversion coefficient in the phosphate glass makes high gain amplifiers possible for very high Er^{3+} concentrations [1]. The noise figures at 1530nm, 1535nm, 1550nm and 1565nm are 6.3dB, 6.1dB, 5.3dB, and 4.8dB, respectively, which can be further reduced by reducing the insertion loss. The current over-all single pass insertion loss is 3dB. Figure 2 shows that greater than 15dBm output power was obtained over the C-band when the input power is 0dBm. The output power increased to 17.5 dBm when the pump power increased to 1.5W.

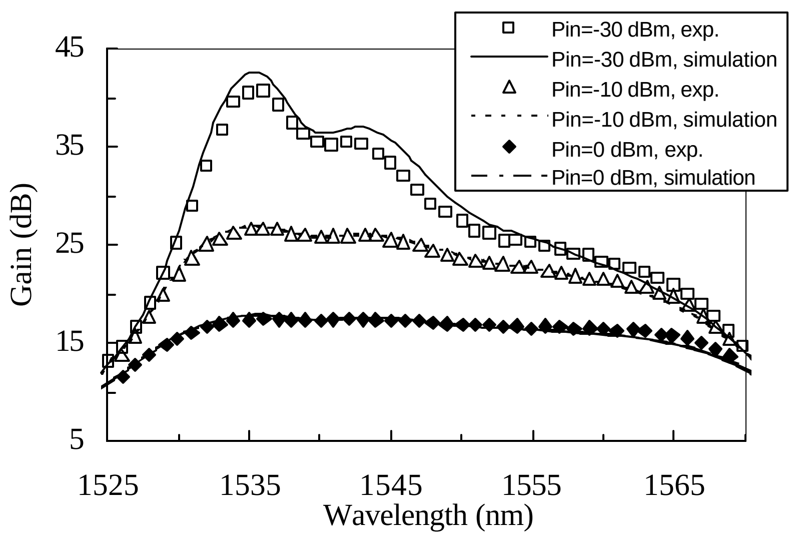

Figure 2. Measured and calculated gain spectra with various input signal power

A theoretical model was developed to simulate our multi-mode pumped amplifiers by using the modified rate equations and effective beam propagation method (BPM). Given the pump $P_p(z = 0)$ and signal $P_s(z = 0)$ powers, the local populations N_i are obtained by numerically solving rate equations. The pump absorption coefficient $a[N_i(P_p,P_s)]$ and the signal gain $g[N_i(P_p,P_s)]$ are computed by equations

$$a[[N_{1,5,6}(P_P(z), P_S(z))] = \sigma_{56}(\nu_p)N_5(z) - \sigma_{65}(\nu_p)N_6(z) + \sigma_{13}(\nu_p)N_1(z) + \alpha_P \quad (1)$$

$$g[N_{1,2}(P_P(z), P_S(z))] = \Gamma_S[\sigma_{21}(\nu_S)N_2(z) - \sigma_{12}(\nu_S)N_1(z)] - \alpha_S \quad (2)$$

Here N_i (i = 1~ 6) are populations at different levels, σ_{ij} are absorption and/or emission cross sections between i- and j-states, Γ_S is the signal overlap factor, and $\alpha_{S,P}$ are propagation losses for signal and pump, respectively. Given the value of $a[N_i(P_p,P_s)]$ at z, the BPM then computes the full transverse distribution of the pump at z + Δz where Δz is 1 micron. The local pump power distribution; pump power absorption of the core, and the inversion rate of Er^{3+} ions along the fiber were iteratively calculated with a step distance of 1 micron until the desired fiber length is reached. With the knowledge of the local gain for signal $g[N_i(P_p,P_s)]$ the gain of the signal can be integrated numerically.

The simulated gain performance agrees closely with the experimental results as indicated in Figure 2. The core in the short fiber absorbed approximately 15% of the multi-mode pump. The model shows that such high absorption in such a short fiber is attributable to the high absorption coefficient of the core. Furthermore, the model indicates that an absorption efficiency of 30% is achievable with proper fiber design, indicating the pump power can be reduced to approximately 0.5W.

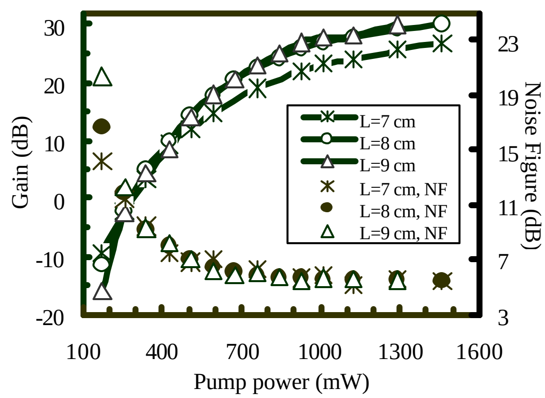

Figure 3. Gain and noise figure vs. pump power at 1550nm

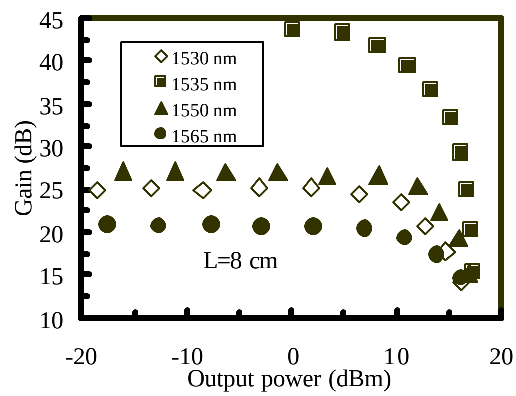

Figure 4. Gain saturation with 1W pump

Figure 3 illustrates the net gain and noise figure versus the pump power at 1550nm for different fiber lengths. The input signal power was –30dBm. Figure 3 indicates that the optimum fiber length is around 8cm. Figure 4 shows the gain saturation at 1530nm, 1535nm, 1550nm, and 1565nm for the 8cm-long fiber excited with 1W pump power. The saturation output power (3dB compression) at 1535nm, 1550nm and 1565nm are 11dBm, 12.5dBm and 14dBm, respectively. The output saturation power is 2dBm higher when the fiber is excited with 1.5W pump power. Increasing the core diameter of the fiber can further increase the output saturation power.

4. Conclusions

In conclusion, a multi-mode pumped fiber amplifier has been successfully developed using newly developed erbium-doped phosphate fibers. A net gain of 43dB at 1535nm, 27dB at 1550nm, and 21dB over the C-band was achieved from an 8 cm-long fiber excited with a 1 W 975 nm broad area laser diode. Output powers of greater than 15dBm have been obtained with 0dBm input signal. The theoretical model indicates that the pump power can be reduced to approximately 0.5W with optimum fiber design. This new type of compact, low cost, and high performance amplifier will play an important role for deployment of low cost metro and access fiber optical networks.

5. References:

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