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# OPTICAL AMPLIFIERS AND THEIR APPLICATIONS

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# +20 dBm Erbium Power Amplifier Pumped by a Diode-Pumped Nd:YAG Laser

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Abstract: Efficient energy transfer has been demonstrated in an Er/Yb co-doped phosphorus doped silica fiber for the first time. This has indirectly allowed the use of reliable, high power AlGaAs diode laser arrays as the semiconductor pump source through the use of a diode-pumped Nd:YAG (DPL) laser operating at 1064 nm. Small signal gains of 40 dB and output powers of 69 mW (+18.4 dBm) have been observed with a single DPL. Bi-directional pumping with two DPL's has yielded an output power of 145 mW (+21.5 dBm).

Introduction: Much of the recent discussion regarding the systems deployment of the erbium optical amplifier has focussed on the pump source. 980 and 1480 nm pump sources are widely considered to be the most viable options and each have advantages and disadvantages with regards to efficiency, intrinsic noise figure, pump laser power and lifetime. Co-doped fibers are an attractive means of alleviating constraints on the pump source wavelength by using a sensitizer with a broad absorption band. Yb is especially attractive in this regards as it exhibits an intense broad absorption between 800 and 1080 nm, spanning several convenient pump wavelength source options. An efficient amplifier using an $Er^{3+}/Yb^{3+}$ co-doped phosphate glass fiber has previously been demonstrated [1]. However, these fibers suffer several drawbacks, including poor mechanical strength, higher intrinsic loss, as well as a thermal and index mismatch when compared to silica fibers. Previous experiments with co-doped silica based fibers have demonstrated the inefficiency of the energy transfer process [2]. The limiting factor is the relatively long lifetime of the $^4I_{11/2}$ band of Er, around 5 microseconds in silica. This allows significant back-transfer to $Yb^{3+}$ with a corresponding loss of inversion. The $Yb^{3+}$ to $Er^{3+}$ energy transfer efficiency is extremely host dependent, with a high phonon energy host being preferred to decrease the intermediate $^4I_{11/2}$ level lifetime of erbium [3]. For example we have measured an initial energy transfer efficiency (approaching zero erbium inversion) of only 5% in an Er/Yb germanosilica fiber while the initial transfer efficiency is 90% in a phosphate glass host. We have found that small amounts of phosphorus, when added to silica based fibers, mimics the spectroscopic environment of the phosphate glass host. Such fibers exhibit greatly improved properties relative to the previously fabricated phosphate glass fibers.

We have chosen to pump on the long-wavelength tail of the $Yb^{3+}$ absorption using a diode-pumped Nd:YAG laser (DPL) operating at 1064 nm. The advantages of the DPL are the use of mature, efficient and high-power AlGaAs diode lasers, the high beam quality and the scalability of this approach with pump array size. Besides the obvious frequency conversion, the DPL is also a brightness converter, allowing up to several hundred milliwatts to be coupled from a single pump source into single-mode fiber. Unlike direct diode excitation, this approach is directly scalable with non-diffraction limited pump array size.

Fiber Fabrication and Spectroscopy:
The phosphorus doped silica fibers were fabricated by the solution doping process[4]. A phosphosilicate frit is deposited, via the conventional MCVD process, at a temperature to ensure complete oxidation and deposition, without fusion to a glass. An aqueous solution of high purity rare-earth and aluminum chlorides is diffused into the frit, with the resulting fiber ion concentration being proportional to solution concentration. The phosphosilicate frit is heated in the presence of $Cl_2$ and/or $O_2$ to remove the solvent. The frit is sintered to a glass, trapping the dopant ions. The preform collapse and fiber drawing are then done in the conventional fashion. The phosphate fibers were prepared by the rod-in-tube method from commercially available phosphate glasses.

Fluorescence spectra from four fibers, measured under 820 nm excitation, are shown in figure 1. The peak fluorescence wavelengths, and integrated linewidths are listed in table 1. Several important features are to be noted. Firstly, the spectra of fibers 1 (Er only) and #2 are nearly identical, indicating that the emission spectrum is independent of the presence of Yb. Florescence from the phosphate glass fiber (#4) is significantly narrower and shifted to longer wavelengths. The emission spectrum of the phosphorus-doped silica fiber (#3) is nearly identical to that of the pure phosphate, although the linewidth is in fact slightly narrower. We attribute this spectral narrowing to a reduced site-to-site variation in this host. Significantly, the heavily $Al_2O_3$ doped fiber (#2) appears to have lost the spectral characteristics of the phosphorus doped silica fiber.

Amplifier Performance: A diagram of the amplifier system is shown in figure 2. We have observed 40 dB of small-signal system gain and 50 mW (+17.0 dBm) of output power in a counter-propagating configuration. The active section as well as some of the components are not yet optimized, for example, we have measured the total system loss to be 5 dB. Consequently, the internal fiber small signal gain is 45 dB. The noise figure, corrected for laser diode RIN and input coupling losses, is in the range of 3-4 dB in the saturated power amplifier regime. For additional power amplifier measurements, we used the configuration shown in figure 2 minus the input and output isolators. Pumping with a single DPL in the counter-propagating configuration, we have observed a power output of 69 mW (+18.4 dBm) for 200 mW absorbed (34.5% slope efficiency). Using two DPL's in a bi-directional pumping configuration, we have observed 145 mW (+21.5 dBm) of output power for 365 mW absorbed, giving a slope efficiency of 39.7%. These output powers and/or efficiencies should continue to increase with continued optimization of fiber composition as well as decreased splice losses in the system.

Conclusions: An efficient $Er^{3+}/Yb^{3+}$ co-doped silica based fiber has been demonstrated for the first time. The efficiency of the phosphate glass host has not only been duplicated, but surpassed, with a relatively small amount of phosphorus doped into the silica host. Diode-pumped Nd:YAG laser pumping of this fiber at 1064 nm has yielded gains in excess of 40 dB and output powers exceeding +20 dBm. This Er/Yb co-doped amplifier is thus able to utilize highly non-diffraction limited AlGaAs diode laser arrays in a directly power scalable approach.

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**References:**

1. S.G. Grubb, R.S. Cannon, T.W. Windhorn, S.W. Vendetta, P.A. Leilabady, D.W. Anthon, K.L. Sweeney, W.L. Barnes, E.R. Taylor and J.E. Townsend' *Optical Fiber Communication Conference*, 1991 Technical Digest Postdeadline Papers, (Optical Soc. of America, Washington DC, 1991), Paper PD7, pp. 31-34.

2. W.L. Barnes, S.B. Poole, J.E. Townsend, L. Reekie, D.J. Taylor, and D.N. Payne, *J. Lightwave Technology*, 7(10), 1461 (1989).

3. V.P. Gapontsev et. al. *Opt. Commun.* 46 226 (1983).

4. J.E. Townsend, W.L. Barnes, K.P. Jedrzejewski, and S.G. Grubb, submitted to *Electronics Letters*.

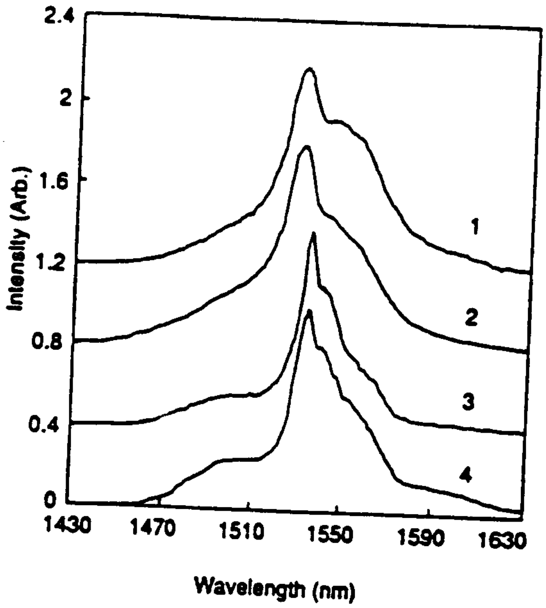


**Figure 1 :** Fluorescence spectra of fibers excited with 820 nm radiation. The compositions are given in Table 1.

| Fiber | Core Composition (mol %) | N.A. | $Er^{3+}$ (ppm) | $Yb^{3+}$ (ppm) |
|---|---|---|---|---|
| #1 | $P_2/Al_2/Si$ 2/4/94 | 0.15 | 800 | 0 |
| #2 | $P_2/Al_2/Si$ 2/11/86 | 0.23 | 550 | 7,500 |
| #3 | $P_2/Al_2/Si$ 11/1/87 | 0.15 | 3000 | 28,000 |
| #4 | $P_2/Al_2/Si$ 53/8.6/0 | 0.14 | 5,000 | 80,000 |

**Table 1**

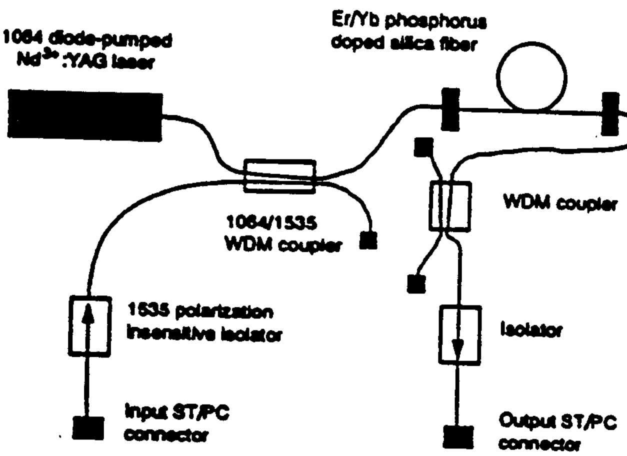


**Figure 2 :** Schematic of the diode-pumped Nd:YAG Er/Yb co-doped amplifier system.

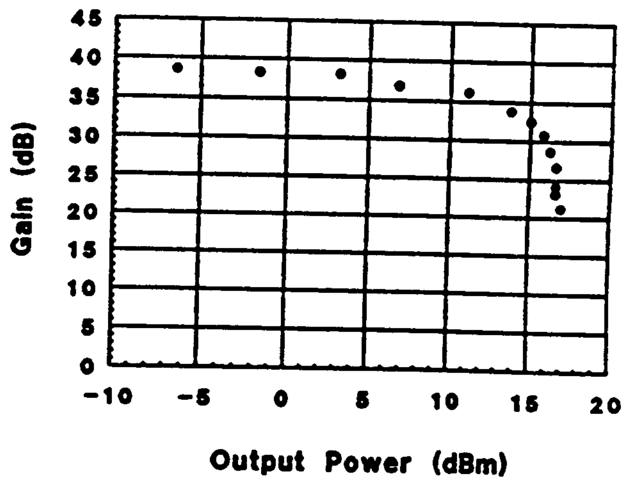


**Figure 3 :** System gain versus output power in a counter-propagating configuration.