ductor laser amplifier," *IEEE J. Quantum Electron.*, vol. QE-23, pp. 1010-1020, June 1987.

[11] D. A. Kleinman and R. C. Miller, "Band-gap renormalization in semiconductor quantum wells containing carriers," *Phys. Rev. B*, vol. 32, pp. 2266-2272, Aug. 15, 1985.

[12] M. J. Adams, J. V. Collins, and I. D. Henning, "Analysis of semiconductor laser optical amplifiers," *IEE Proc.*, vol. 132, pt. J., pp. 58-63, Feb. 1985.

[13] M. G. Oberg, and N. A. Olsson, "Wavelength dependence of noise figure of a travelling-wave GaInAsP/InP laser amplifier," *Electron. Lett.*, vol. 24, pp. 99-100, Jan. 21, 1989.

[14] B. Mikkelsen, D. S. Olesen, K. E. Stubkjaer, Z. Wang, A. J. Collar, and G. D. Henshall, "Temperature-Dependent Gain and noise of 1.5 μm Laser Amplifiers," *Electron. Lett.*, vol. 25, pp. 357-359, Mar. 2, 1989.

+21 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 42 dB and output powers of 71 mW (+18.5 dBm) have been observed with a single DPL. Bidirectional pumping with two DPL's has yielded an output power of 130 mW (+21 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 the most widely considered 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 Er/Yb co-doped silica fibers showed inefficient energy transfer [2]. The limiting factor was the relatively long lifetime of the $^4I_{11/2}$ band of Er, around 3 μs 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 nondiffraction limited pump array size. Ultrahigh power amplifiers with output powers have been demonstrated in 1.48-μm-pumped erbium amplifiers. These amplifiers, however, require four separate pump sources multiplexed with polarization preserving fiber and bulk beamsplitting cubes. Besides the insertion losses of these devices, they are liable to introduce significant reflections in this high gain amplifier system, both contributing to a degraded noise performance.

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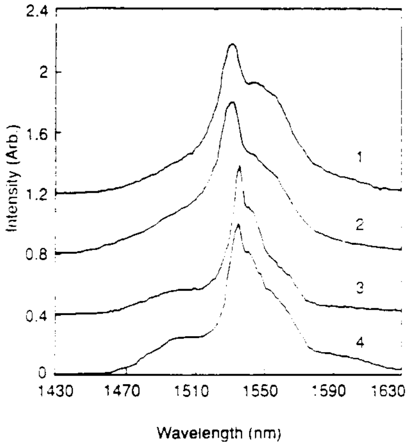

Fig. 1. Fluorescence spectra of Er- and co-doped Er/Yb fiber under 810 nm excitation. The fiber compositions are explained in the text.

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 sufficient 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 rare-earth 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 Fig. 1. The peak fluorescence wavelengths, and integrated linewidths are listed in Table I. 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. Fluorescence 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 Fig. 2. Each end of the Er/Yb co-doped fiber is connected to a WDM coupler and a polarization insensitive isolator. All values of small signal gain as well as output power values are system values, that is measured at the input and output ST connectors. We observe 42 dB of small-signal system gain and 71 mW (+18.5 dBm) of output power with a single DPL pump source in a counter-propagating configuration, as shown in Fig. 3.

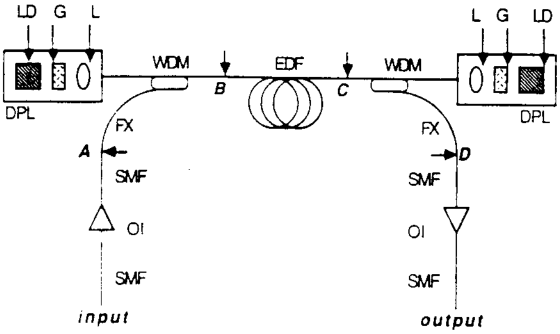

Fig. 2. Experimental diagram for the co-doped Er/Yb DPSS-pumped optical amplifier. The components are as follows: DPL: diode-pumped Nd:YAG laser. LD: AlGaAs diode laser array. *G*: Nd:YAG gain medium. *L*: lens. WDM: wavelength division multiplexing coupler. EDF: Er/Yb co-doped fiber. OI: Optical isolator. FX: Corning Flexcore 1064 single-mode fiber. SMF: Corning SMF-28 fiber.

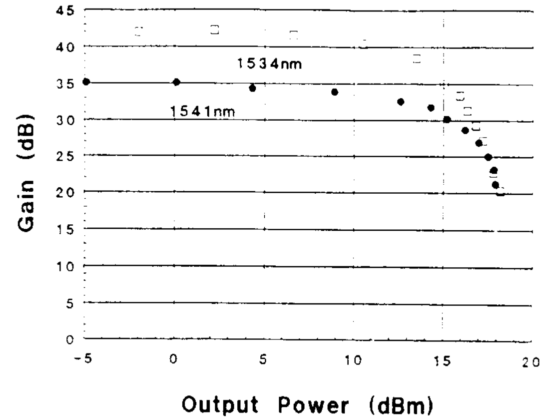

Fig. 3. System gain versus output power for a single DPL-pumped Er/Yb co-doped amplifier. The pump source was counter-propagating with respect to the signal.

TABLE I
CORE COMPOSITIONS, PEAK FLUORESCENCE WAVELENGTH, AND INTEGRATED LINEWIDTHS FOR THE FOUR FIBERS WHOSE FLUORESCENCE SPECTRA ARE SHOWN IN FIG. 1

Fiber	Core Composition (mole %)	λ_p (nm)	$\Delta\lambda$ (nm)
1	P_2 Al_2/Si : 2/4/94	1532	52
2	P_2 Al_2/Si : 2/11/86	1531	52
3	P_2 Al_2/Si : 8/5/86	1535	34
4	P_2 Al_2/Si : 53/9/0	1534	42

Using two DPL's in a bidirectional pumping configuration, we have obtained up to +21.5 dBm of output power as shown in Fig. 4, measured at a signal input wavelength of 1542 nm. There was approximately 390 mW of pump light of coupled pump light into the active fiber for the bidirectional pumping case, giving an optical conversion efficiency of 38%. Note that the gain is still above 30 dB at an output power of +20 dBm. The active Er/Yb fiber has not yet been matched well to the fiber characteristics of the WDM couplers and we observe 0.5-1.0 dB of splice loss at each of these points. We have not yet optimized the dopant ratios or the numerical aperature of the co-doped amplifier fiber. The noise performance of the co-doped amplifier does not appear to be significantly different from the 980 nm pumped amplifier case. Fig. 5 shows the gain bandwidth response of the

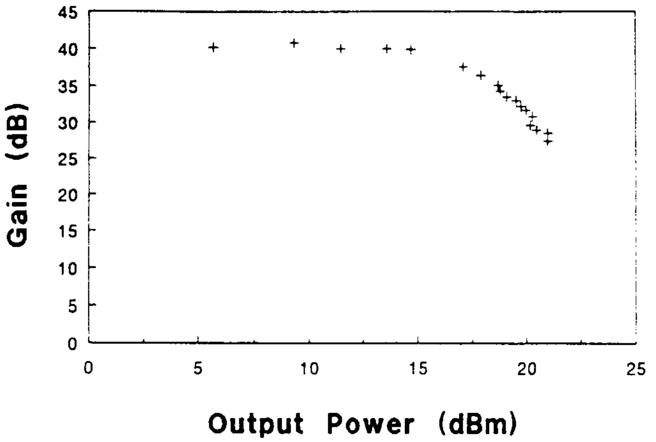

Fig. 4. System gain versus output power for a dual-pumped amplifier in a bidirectional pumping configuration.

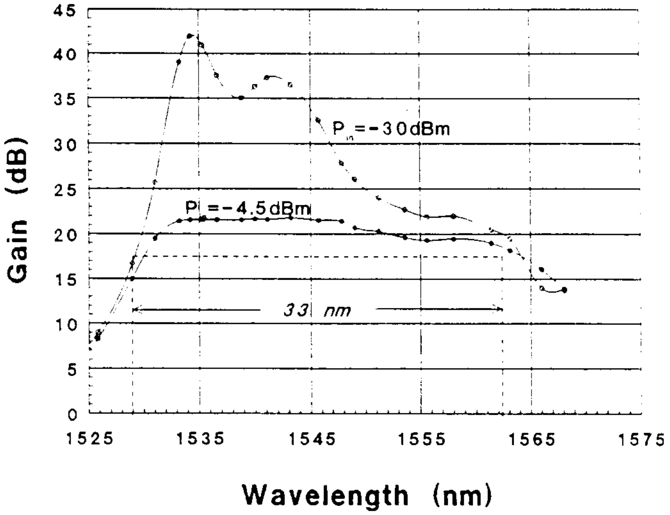

Fig. 5. Gain bandwidth curves for low (−30 dBm) and high (−4.5 dBm) input signal levels.

co-doped Er/Yb amplifier at both high and low signal input levels. Fig. 6 shows the noise figure versus input signal power, corrected for diode laser RIN and input coupling losses. Initial CATV experiments show no significant distortions (CSO and CTB < -60 dBc) introduced by the co-doped amplifier [5].

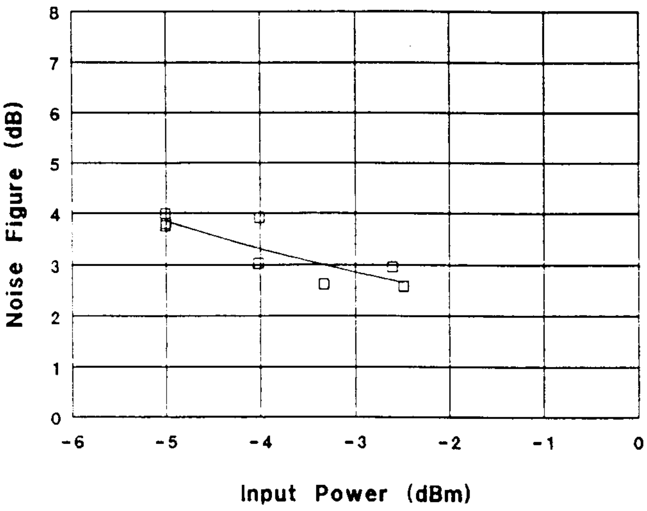

Fig. 6. Noise figure versus input signal level for the Er/Yb co-doped amplifier.

CONCLUSIONS

An efficient Er^{3+}/Yb^{3+} co-doped silica based fiber has been demonstrated for the first time. Diode-pumped Nd:YAG laser pumping of this fiber at 1064 nm has yielded gains in excess of 40 dB and output powers of +21 dBm. This Er/Yb co-doped amplifier is thus able to utilize highly nondiffraction limited AlGaAs diode laser arrays in a directly power scalable approach, in contrast to direct diode pumping.

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, *Opt. Fiber Commun. Conf.*, 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 Technol.*, vol. 7, p. 1461, Oct. 1989.

[3] V. P. Gapontsev *et al.*, *Opt. Commun.*, vol. 46, 226, 1983.

[4] J. E. Townsend, W. L. Barnes, K. P. Jedrzejewski, and S. G. Grubb, *Electron. Lett.*, vol. 27, no. 21, p. 1958, 1991.

[5] P. A. Leilabady, S. G. Grubb, K. L. Sweeney, R. S. Cannon, S. V. Vendetta, T. H. Windhorn, G. Tremblay, and G. S. Maurer, *ECOC Conf.*, Paris, France, Sept. 1991, Postdeadline paper PD2, 1991.