Compact multimode pumped erbium-doped phosphate fiber amplifiers

Shibin Jiang, MEMBER SPIE
Sergio B. Mendes
Yongdan Hu
Gualtiero Nunzi-Conti
Arturo Chavez-Pirson
Yushi Kaneda
Tao Luo
Qingyun Chen
Sandrine Hocde
Dan T. Nguyen, MEMBER SPIE
NP Photonics, Incorporated
9030 South Rita Road
Tucson, Arizona 85747
E-mail: jiang@npphotonics.com

Ewan Wright
NP Photonics, Incorporated
9030 South Rita Road
Tucson, Arizona 85747
and University of Arizona
Optical Sciences Center
Tucson, Arizona 85721

Jiafu Wang
Wenyan Tian, MEMBER SPIE
Thomas Nikolajsen
NP Photonics, Incorporated
9030 South Rita Road
Tucson, Arizona 85747

Nasser Peyghambarian, MEMBER SPIE
NP Photonics, Incorporated
9030 South Rita Road
Tucson, Arizona 85747
and University of Arizona
Optical Sciences Center
Tucson, Arizona 85721

Abstract. The performance of compact multimode pumped erbium-doped phosphate fiber amplifiers is presented. A fiber amplifier with a small signal net gain of 41 dB at 1535 nm and 21 dB over the full C-band is demonstrated using a newly developed 8-cm-long erbium-doped phosphate fiber excited with a 1-W, 975-nm multimode laser diode. A theoretical model is developed for the multimode pumped amplifier based on modified rate equations and an effective beam propagation method. Close agreement between experimental and modeling results is observed.
[DOI: 10.1117/1.1600460]

Subject terms: erbium-doped fiber amplifier; ytterbium; multimode pumped; phosphate fiber.

Paper AWGE012 received Jan. 15, 2003; accepted for publication Mar. 12, 2003.

1 Introduction

Erbium-doped fiber amplifiers (EDFAs) have revolutionized the modern telecommunication industry since the late 1980s.[1] Up-to-date, single-mode lasers are most often chosen as pump sources for such EDFAs. However, multimode broad-area laser diodes were introduced to pump the single-mode core via its surrounding cladding as early as the 1970s.[2,3] Compared with its single-mode counterpart, this approach can alleviate the stringent alignment requirement and have higher amplifier output power because a few watts instead of milliwatt pump power is readily available from a multimode broad-area diode. Recently, two distinct advanced cladding pumping techniques have been developed.[4,5] High-power EDFAs based on these techniques have been reported thereafter.[6,7] However, these silica-based high-power EDFAs employ tens of meters of erbium-doped fiber even when a relatively high erbium concentration is used.[6] This is limited by the fact that silica glass cannot support very high erbium concentration without deleterious ion-ion interactions because of its rigid glass network.[8] On the other hand, phosphate glass has exhibited excellent solubility for rare-earth ions.[9] In our previous work, we demonstrated single-mode pumped erbium-doped phosphate glass fiber amplifiers with gain per unit length as high as 5 dB/cm.[10] We report a compact multimode pumped fiber amplifier using a newly developed double-clad phosphate glass fiber. A net gain of 41 dB at 1535 nm, 27 dB at 1550 nm, and 21 dB over the C-band was achieved from an only 8-cm-long fiber excited with a 1-W, 975-nm multimode broad-area laser diode pump. A theoretical model was also developed to simulate our amplifier performance based on modified rate equations and an effective beam propagation method (BPM), showing excellent agreement between experimental and modeling results.

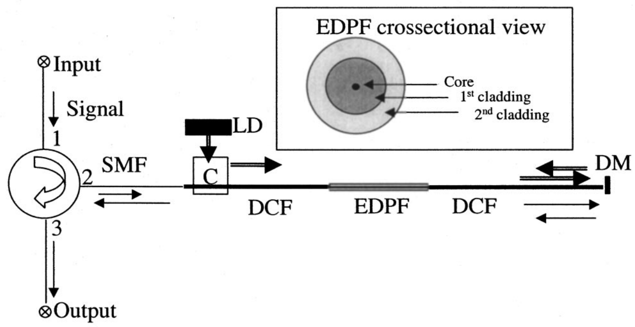

Fig. 1 Schematics of the multimode pumped amplifier. SMF is a Corning single-mode fiber SMF-28; LD is a Spectral Physics 50-μm multimode pump laser diode; C is a proprietary pump coupler; DCF is a double-clad fiber; EDPF is the erbium-doped phosphate fiber; and DM is the dielectric mirror.

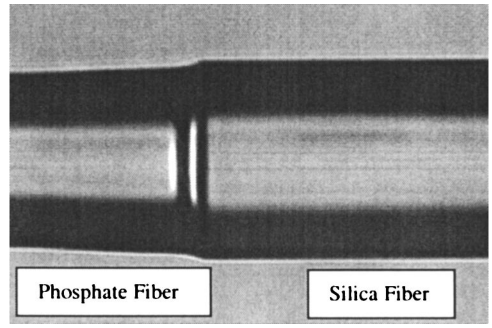

Fig. 2 Fusion spliced joint between phosphate and silica fibers.

2 Amplifier Design

Figure 1 shows the layout of our amplifier in a reflective geometry by using a circulator. Pump light from a Spectra-Physics multimode 50-μm broad-area laser diode is coupled into the first cladding of a passive double-clad fiber (DCF) through a proprietary coupler.[11] The DCF is then fusion-spliced to an 8-cm erbium-doped phosphate fiber (EDPF). A signal is launched from port 1 of the circulator and directed to the EDPF through port 2. A dielectric mirror is coated on the tip of the DCF fusion-spliced to the other side of the EDPF and is used to highly reflect both the pump and the signal. Most of the residual pump is immediately dumped when it reaches the SMF and is further reduced to a -60-dBm level by the built-in isolator in the circulator en route to the output of the amplifier. The inset in Fig. 1 shows a cross sectional view of the EDPF. As shown in the figure, the core, the first, and the second cladding are all axially symmetric. And the numerical apertures of the core and the first cladding were calculated to be 0.145 at 1550 nm and 0.24 at 980 nm, respectively. The propagation loss at 1310 nm was measured to be 0.09 dB/cm, which is a significant improvement from what we reported before.[10] This single-mode double-clad EDPF was fabricated with no plastic coating applied to the fiber. A high erbium concentration codoped with ytterbium was used to provide a high absorption coefficient for the pump. Different from our previous work,[10] 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 alkali ions (e.g., K^+, Na^+, and Li^+), which are contained in most commercial phosphate glasses. Therefore, fusion splicing between the EDPF and the DCF can be reliably achieved, as illustrated in Fig. 2. 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 on theoretical modeling and spectral characterization results, especially after considering the cooperative up conversion. Er^{3+}/Yb^{3+}-doped phosphate glasses and undoped cladding glasses were melted in a platinum crucible using high purity starting chemicals. To ensure good glass quality and to provide all necessary parameters for our theoretical model, detailed glass property characterizations were also performed. The refractive indices of the glass samples were measured with a prism coupler at 632.8, 980, 1300, and 1550 nm. The absorption and emission cross sections were determined to be $0.75\times10^{-20}\,cm^2$ and $0.82\times10^{-20}\,cm^2$ at 1534 nm, respectively.

3 Amplifier Characterization and Theoretical Simulation

Amplifier performance was evaluated experimentally using fibers with lengths of 7, 8, and 9 cm. This work mainly reports the results obtained from the 8-cm-long EDPF. Excluding the circulator and the dielectric mirror, the single-pass insertion loss with this EDPF was measured at 1310 nm to be 3 dB. Almost 1/3 of this insertion loss was from the propagation loss of the EDPF. Figure 3 illustrates the measured and simulated amplifier gain spectra from the 8-cm-long EDPF at signal input powers of -30, -10, and 0 dBm with a 1-W pump power from the broad-area laser diode. A peak gain of 41 dB was achieved at 1535 nm with a -30-dBm input signal. At the -30-dBm input signal level, the noise figures at 1530, 1535, 1550, and 1565 nm were measured to be 6.3, 6.1, 5.3, and 4.8 dB, respectively. Figure 3 shows that greater than 15-dBm output power could be delivered over the whole C-band when the input power was 0 dBm. The output power increased to 17.5 dBm when the pump power increased to 1.5 W.

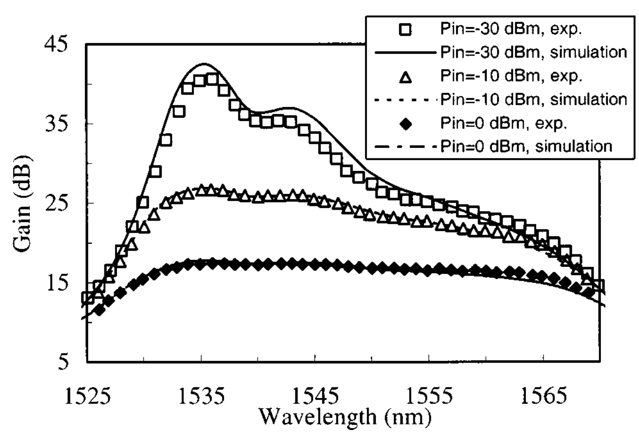

Fig. 3 Measured and simulated gain spectra with various input signal powers.

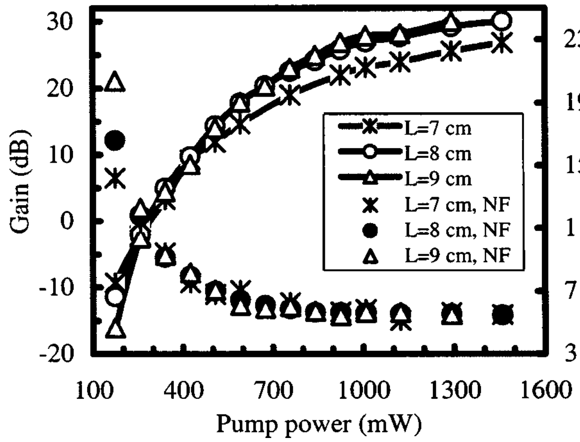

Fig. 4 Gain and noise figure versus pump power at 1550 nm.

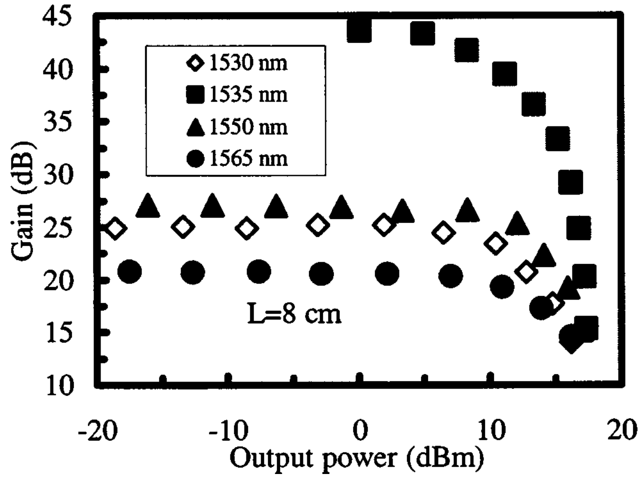

Fig. 5 Gain saturation with a 1-W pump.

A theoretical model was developed to simulate our multimode 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 $\alpha[N_i(P_p,P_s)]$ and the signal gain $g[N_i(P_p,P_s)]$ are computed by equations

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

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

Here N_i ($i=1$ to 4 stands for Er^{3+} levels $^4I_{15/2}$, $^4I_{13/2}$, $^4I_{11/2}$, and $^4I_{9/2}$, respectively; and $i=5$ to 6 stands for Yb^{3+} levels $^2F_{7/2}$ and $^2F_{5/2}$, respectively) are populations at different levels; σ_{ij} are absorption or emission cross sections between *i*- and *j*-states; Γ_S is the signal overlap factor; $\alpha_{S,P}$ are background propagation losses for signal and pump, respectively; and $\nu_{s,p}$ are frequencies of signal and pump, correspondingly. Given the value of $\alpha[N_i(P_p,P_s)]$ at *z*, the BPM then computes the full transverse distribution of the pump at $z+\Delta z$, where Δz is 1 μm. The local pump power distribution, pump power absorption of the core, and the inversion rate of Er^{3+} ions along the fiber are calculated with a step distance of 1 μm 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 whole procedure is iterated until convergence is reached.

The simulated gain performance agrees closely with the experimental results as indicated in Fig. 3. According to our modeling results, the core in the 8-cm EDPF absorbed approximately 15% of the multimode pump. The model also showed that such high absorption in such a short fiber was attributable to the high pump absorption coefficient of the core. Furthermore, the model indicated that an absorption efficiency of 30% is achievable with an optimized EDPF design in terms of doping concentrations and fiber geometry.

Figure 4 illustrates the net gain and noise figure versus the pump power at 1550 nm for different fiber lengths. The input signal power was −30 dBm. Figure 4 indicates that the optimum fiber length is around 8 cm. Figure 5 shows the gain saturation at 1530, 1535, 1550, and 1565 nm for the 8-cm-long fiber excited with 1-W pump power. The saturation output power (3-dB compression) at 1535, 1550, and 1565 nm are 11, 12.5, and 14 dBm, respectively. The output saturation power is 2 dB higher when the fiber is excited with 1.5 W pump power.

4 Discussion and Conclusions

In conclusion, a multimode pumped fiber amplifier is successfully developed using newly developed erbium-doped phosphate fibers. A net gain of 41 dB at 1535 nm, 27 dB at 1550 nm, and 21 dB over the C-band is achieved from an 8-cm-long fiber excited with a 1-W 975-nm broad-area laser diode. The theoretical model indicates that the pump power can be reduced to approximately 0.5 W with optimum EDPF designs.

As shown in Fig. 1, the dielectric mirror can be designed to partially reflect signals at certain wavelengths so that gain flattening can be realized. Both the dielectric mirror and the pump coupler can in principle be directly built on EDPF, making the amplifier design even more compact. This amplifier design is also low cost in nature. For the time being, 980-nm multimode broad-area laser diodes cost about one tenth of a single-mode 980-nm pump in terms of cost per watt of power. For high-power amplifiers beyond 27 dBm, the single-mode pumping approach becomes prohibitively expensive because of the cost of these single-mode diodes and corresponding parts, while a multimode approach offers an already-demonstrated alternative for such high-power amplifiers.[6,7] Furthermore, our unique EDPF costs about one hundredth of conventional silica-based erbium-doped fibers, while it delivers the same amplifier performance. 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.

References

1. E. Desurvire, *Erbium-Doped Fiber Amplifiers: Principles and Applications*, Wiley-Interscience, New York (1994).
2. R. Maurer, U.S. Patent No. 3,808,549 (1974).
3. J. D. Kafka, U.S. Patent No. 4,829,529 (1989).
4. D. J. Ripin and L. Goldberg, ''High efficiency side-coupling of light into optical fibres using imbedded v-grooves,'' *Electron. Lett.* **31**(25), 2204–2205 (1995).
5. V. P. Gapontsev and I. E. Samartsev, U.S. Patent No. 5,999,673 (1999).
6. L. Goldberg, G. M. Williams, and J. Delavaux, ''Multi watt amplifier and laser concepts, design and limitations,'' *OFC'02*, Anaheim, CA (2002).
7. V. P. Gapontsev, I. E. Samartsev, V. Fomin, N. S. Platonov, S. V. Chemikov, and J. R. Taylor, ''High power fiber lasers—the revitalisation of laser technology,'' *LEOS'97* **2**, 380 (1997).
8. Y. Hu, S. Jiang, G. Sorbello, T. Luo, Y. Ding, B. Hwang, J. Kim, H. Seo, and N. Peyghambarian, ''Numerical analyses of the population dynamics and determination of the upconversion coefficients in a new high erbium-doped tellurite glass,'' *J. Opt. Soc. Am. B* **18**(12), 1928–1934 (2001).
9. B. C. Hwang, S. Jiang, T. Luo, J. Watson, G. Sorbello, and N. Peyghambarian, ''Cooperative upconversion and energy transfer of new high Er^{3+}- and Yb^{3+}/Er^{3+}-doped phosphate glasses,'' *J. Opt. Soc. Am. B* **17**(5), 833–839 (2000).
10. Y. Hu, S. Jiang, T. Luo, K. Seneschal, M. Morrell, F. Smektala, S. Honkanen, J. Lucas, and N. Peyghambarian, ''Performance of high-concentration Er^{3+}/Yb^{3+}-codoped phosphate fiber amplifiers,'' *IEEE Photonics Technol. Lett.* **13**(7), 657–659 (2001).
11. Y. Kaneda, S. Mendes, and S. Jiang, ''Total internal reflection (TIR) coupler and method for side-coupling pump light into a fiber,'' U.S. Patent in procurement, filed on August 30, 2001.