Development of Er/Yb Co-doped Fiber for High-Power Optical Amplifiers

by Keiichi Aiso *, Yoshio Tashiro *2, Tsuneo Suzuki *3 and Takeshi Yagi *

ABSTRACT The increasing capacity of wavelength-division multiplexing (WDM) transmission systems requires higher optical output power of erbium doped fiber amplifiers (EDFAs). Higher output causes in the EDFA adverse nonlinear effects --four-wave mixing (FWM) and cross-phase modulation (XPM) etc.-- that result in signal distortion. In the past fiber parameters of Er-doped fibers (EDFs) have been optimized from the standpoint of improving amplification efficiency, but designs that improve efficiency increase nonlinearity. This makes it difficult to achieve low nonlinearity with EDF. Here the authors have developed fibers that are co-doped with erbium and ytterbium. This Er, Yb co-doped fiber (EYDF) successfully realizes low nonlinearity without degrading amplification efficiency, and when pumped using a 1480-nm laser diode, EYDFAs achieve both lower nonlinearity and higher output power.

1. INTRODUCTION

There has been a rush to expand the capacity of telecommunications services resulting from the increased demand due mainly to the Internet. This has been achieved both by increasing the number of channels and by expanding the transmission band. Expansion of WDM systems thus makes the capacity and bandwidth of fiber-optic amplifiers key aspects of the system.

Increasing the number of channels of a WDM transmission system requires an increase in total input signal power, resulting in a need for higher output power from EDFAs, which provide batch amplification of 1550-nm band WDM signals.

EDFA output power has grown in step with greater EDF efficiency and increased pumping laser diode power. Furukawa Electric, in an effort to achieve good conversion efficiency under highly pumped conditions, is working to optimize EDF fiber parameters and has achieved a quantum conversion efficiency from pumping power to signal power of 90% or more [1]. The output power of 1480-nm laser diodes has been increased [2], and the technologies of wavelength multiplexing and polarization multiplexing of the laser diodes have been applied to obtain increased pumping power [3]. By these means it has been possible to design EDFAs with signal power of 1.5 W [4].

Several high-power pump sources have also been proposed for laser diodes of other than 1480 nm. There is, for example, a report of a 1480-nm cascaded Raman resonator (CRR) being used as a pump source [5].

In addition to 1480 nm, 980 nm is also in general use as the pumping wavelength for EDF, but the pump-to-signal conversion efficiency is lower than for 1480 nm and the absorption spectrum is also narrower. This makes wavelength multiplexing difficult, as well as disadvantageous in terms of increasing the output power of EDF.

To broaden the range of pumping power wavelength, consideration was given to EYDF, in which Yb is co-doped with Er. In EYDF, energy transfer from the excited state of Yb to that of Er is utilized to form population inversion between lasing levels of Er and the signal is amplified through stimulated emission. Yb has a wide absorption band from 800 to 1100 nm, and the use of a 1064-nm Nd:YAG laser, and more recently of an Nd-doped double-clad laser, as the pumping light source [6), 7)] has been reported.

As can be seen from the above, the output power of the EDFA is largely dependent on the power of the pumping light source. EDF core diameter, however, ordinarily ranges from a few micrometers to 10 μm at the most, and this restricted cross-section places an inherent limitation on the pumping power that can be coupled. To relax this limitation a double-clad amplifier has been proposed, in which the signal light propagates in single mode in the core and the pumping light propagates in the first cladding around the core in multimode [8), 9)]. Such an amplifier, which is "side-pumped" configuration, is less efficient than a configuration in which the pumping light is directly coupled to the core, but, since it can use Watt-class multimode laser diodes as the pumping source, gives promise of realizing Watt-class amplifier power with comparative ease.

The realization of such Watt-class fiber-optic amplifiers

* Optical Fiber Gr., Research Dept., FITEL-Photonics Lab.
*2 WP Team, FITEL-Photonics Lab.
*3 TF Team, Chiba Optical Fiber Production Dept., Optical Fiber Div.

raises a new problem of generating nonlinear effects in EDF, which in the past was negligible. Accordingly the authors embarked on a study of how to minimize nonlinearity in EDFs for high-power amplifiers without suffering degradation in amplifier efficiency. This paper reports on techniques for reducing nonlinearity in Er-doped fibers for high-power optical amplifiers.

2. REDUCING NONLINEARITY IN EDF

With the increasing number of WDM channels and the higher optical power per channel, there has been a conspicuous increase in such nonlinear optical effects as four-wave mixing (FWM) [10] and cross-phase modulation (XPM) in EDFA [11]. L-band EDFA is also coming to be used in addition to C-band, but because of its smaller gain coefficient it requires a greater length of EDF. This means that nonlinear effects arise more readily in L-band EDFAs than in C-band [12), 13]. The degree of signal distortion due to nonlinear phenomena in EDF may be estimated roughly using Equation (1) [14].

$$\kappa P_0 L_{\mathrm{eff}} = \frac{\kappa P_0}{g}[\exp(gL)-1] = \frac{2\pi}{\lambda}\frac{n_2}{A_{\mathrm{eff}}}\frac{P_0}{g}[\exp(gL)-1] \quad (1)$$

where: κ is the nonlinear coefficient; L_{eff} is the effective length; n_2 is the nonlinear refractive index; A_{eff} is the effective core area; P_0 is the averaged input power per channel; g is the averaged gain coefficient; and L is the length of the EDF.

As will be readily understood from Equation (1), the appearance of nonlinear phenomena can be inhibited by increasing A_{eff} and g. Accordingly the values of P_0 and G (= $\exp(gL)$) are selected in accordance with the EDFA application.

Typically the value of A_{eff} is about an order of magnitude smaller for an EDF than for a conventional single-mode fiber, because relative refractive index difference Δ of EDF is set up higher to improve gain efficiency. Conversely, increasing the A_{eff} of the EDF will result in degradation in the power conversion efficiency (PCE) from pumping power to signal. Accordingly A_{eff} must be optimally designed in accordance with pumping power, so that there is no degradation in PCE.

In order to increase the gain coefficient g in an EDF, the amount of doped Er ion must be increased, but higher Er concentration leads to concentration quenching and a consequent degradation in amplification efficiency. It is generally held that limitation on Er concentration for the occurrence of concentration quenching is reported to be several hundred ppm by weight in the case of a pure SiO_2 host, and about 1,000 wt ppm even for an Al_2O_3-SiO_2 host, which has been co-doped with aluminum to inhibit concentration quenching [15]. For this reason there are limits to the improvement in gain coefficient g that can be made by increasing Er concentration.

Thus when it is desired to use EDF of conventional design in a high-power amplifier, it is very difficult to achieve both low nonlinearity and high conversion efficiency, and it was therefore necessary to adopt a novel design technique.

3. INHIBITING CONCENTRATION QUENCHING IN EDF

If the doping concentration of Er in EDF is increased, the pumping efficiency of the EDFA is reduced because of concentration quenching. This is because when the distance between Er ions decreases, any two adjacent ions excited at the $^4I_{13/2}$ state interact in a process known as cooperative upconversion, whereby energy is transmitted from one ion, which makes a transition to the $^4I_{15/2}$ (ground) state, while the other ion is excited to the $^4I_{9/2}$ state.

The ion excited to the $^4I_{9/2}$ state decays, through a process of nonradiative transition (or multiphonon decay), to the $^4I_{13/2}$ state, with a resultant decrease in quantum conversion efficiency (QCE) [16].

Cooperative upconversion is related to the way in which the Er ions are introduced into the SiO_2 glass network. Er ions have a low level of solubility to SiO_2 glass so that when they are doped to a pure silica core they form clusters, maintaining the charge balance and dissolving into the silica network [17]. This clustering reduces the distance between ions, resulting in cooperative upconversion.

Concentration quenching caused by cluster formation is known as pair-induced quenching (PIQ) [18], and efforts to reduce PIQ involve changing the composition or fabrication method of the core. The most commonly used method of accomplishing this is by co-doping with Al_2O_3. Aluminum ions surround the Er ions to form a solvent shell, thereby adjusting the charge balance and improving the solubility of Er ions to the host. This inhibits clustering of the Er ions. It is known that with a pure SiO_2 host concentration quenching occurs at an Er concentration of several hundred ppm by weight, but that when co-doped with aluminum, concentration quenching is inhibited up to Er concentrations of about 1,000 wt ppm [15]. Recently a report has also appeared of a case in which concentration quenching was inhibited by changing the core host glass to increase Er solubility [19].

4. CO-DOPING WITH Yb TO INHIBIT PIQ

EYDF, which is fiber co-doped with Yb as well as Er, can be pumped by a high-power laser--Nd:YAG, etc.--placing it in contention for use in high-power optical fiber amplifiers [6]. High-power laser diodes are available for both 1480 and 980 nm wavelengths, so that EDF is used in virtually all the optical amplifiers presently used for telecommunications applications. Recently, however, attention is returning to EYDF as a fiber for use in double-clad amplifiers [8].

Figure 1 shows a model of energy levels in an Er-Yb system. In an EYDF, Yb ions are excited by pumping light

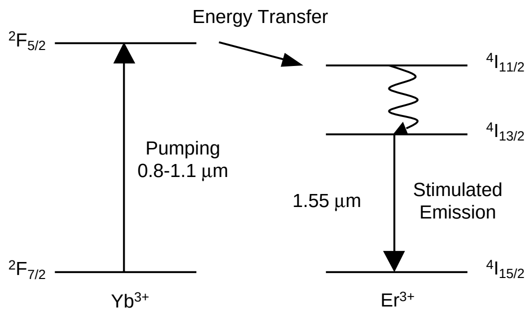

Figure 1 Model of energy levels in an Er-Yb system

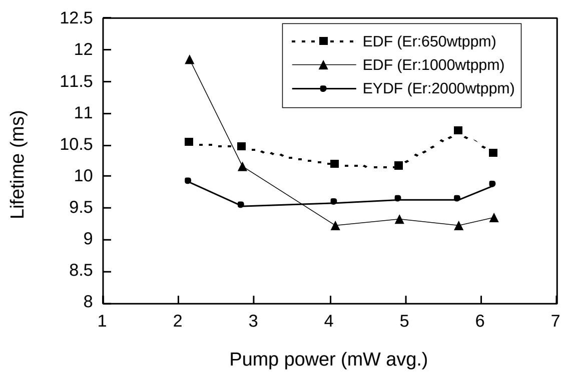

Figure 2 Pumping power dependence of fluorescence lifetime

of 800-1,000 nm to the $^2F_{5/2}$ state, after which Er ions are excited to the $^4I_{11/2}$ state through energy transfer from the Yb ions, while the Yb ions revert to the $^2F_{7/2}$ state.

The Er ions that were excited to the $^4I_{11/2}$ then make a transition to $^4I_{13/2}$ by a nonradiative process, forming a population inversion between the $^4I_{13/2}$ and $^4I_{15/2}$ states and amplifying the incident optical signal by stimulated emission.

Yb ions as well as Er ions have low solubility to a silica host, and since both have about the same ionic radius, they cluster together. Thus the distance between Yb ions and Er ions is reduced and energy transfer proceeds with good efficiency[20].

This means that if a number of Yb ions surround Er ions to form a cluster, the distance separating the Er ions from each other would increase, and this should produce a reduction in the PIQ occurring between Er ions. Recognizing this the authors conducted a study of the inhibiting effect of co-doping with Yb.

The EYDF evaluated in this study had an Er concentration that had been raised to 2,000 wt ppm. To determine whether or not concentration quenching was taking place, measurements of the fluorescence lifetime at the $^4I_{13/2}$ state were made for the EYDF and for two types of conventional EDF, with Er concentrations of 650 and 1,000 wt ppm. When concentration quenching occurred, it was observed that the fluorescence lifetime was shortened. Figure 2 shows the experimental results. For the EDF with an Er concentration of 1,000 wt ppm it was observed that as pumping power increased the fluorescence lifetime became shorter. This is attributed to an increase in the

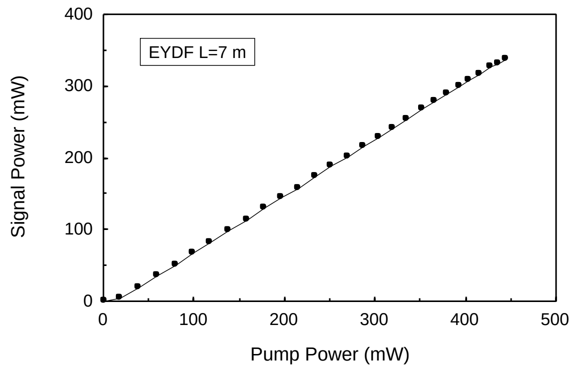

Figure 3 Pumping power dependence of output signal power for EYDF pumped at 1480 nm

number of Er ions in the excited state as the pumping power increased, resulting in cooperative upconversion. It may therefore be concluded that in the EDF with an Er concentration of 1,000 wt ppm, concentration quenching was already occurring. In the EYDF, by contrast, where Er concentration was 2,000 wt ppm, there was no correlation of fluorescence lifetime with pumping power, and it is thought that no marked cooperative upconversion occurred. This result makes it obvious that Yb co-doping makes it possible to increase the limit on Er doping concentration (up to 1,000 wt ppm) that was imposed by concentration quenching in EDF.

5. 1480-nm PUMPED EYDF

As we have pointed out, EYDF has the advantage that it can make use of the broad absorption band of Yb, thereby broadening the range of pumping wavelength. The Er-Yb co-doped amplifiers (EYDFAs) that have heretofore been reported have, obviously enough, been pumped by using a light source with a wavelength matching the absorption band of Yb. In such cases the energy transfer efficiency from the $^2F_{5/2}$ state of the Yb ions to the $^4I_{11/12}$ state of the Er ions is largely dependent on such factors as the concentration ratio of Er to Yb ions and the core material, and we may say that to improve the conversion efficiency from pumping light to signal light, optimization of the composition of the core is indispensable[21]. When the EYDF is excited at 980 nm, it passes through a complex energy transition process involving back-transfer from the $^4I_{11/2}$ state to the $^2F_{5/2}$ state and emissions between the energy states of the Yb, so that the conversion efficiency will inherently be lower than that of EDF.

Accordingly the authors carried out experiments on the pumping of EYDF using a 1480-nm laser diode, which is unaffected by Yb absorption. It is thought that with 1480-nm pumping the Yb ion is virtually inactive optically, and we can expect that it will play a role as a spacer for Er ions, that is to say a PIQ inhibitor.

Figure 3 shows the results of measurements of the pumping power dependence of the output signal power for an EYDF pumped at 1480 nm. The occurrence of concentration quenching brings about a degradation in the power

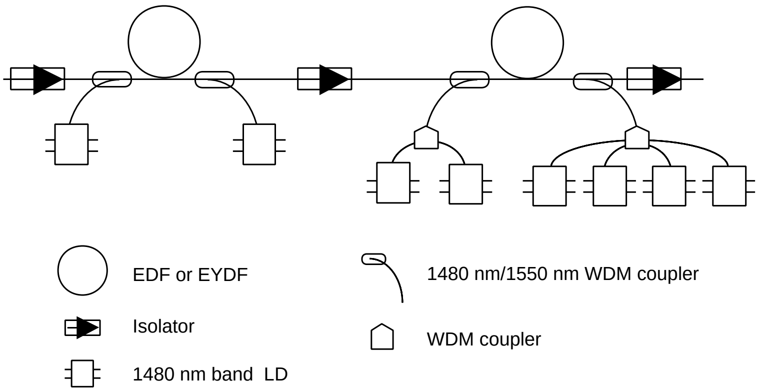

Figure 4 Schematic diagram of WDM amplifier

Table 1 Characteristics of Fibers

Type of fiber	EYDF	EDF
Core composition	Er_2O_3-Yb_2O_3-Al_2O_3-GeO_2-SiO_2	Er_2O_3-Al_2O_3-GeO_2-SiO_2
Er concentration (wt%)	0.2	0.065
Peak absorption (dB/m)@1530 nm	22.7	2.4
MFD (um)@1550 nm	7.0	5.8
Chromatic dispersion (ps/nm/km)@1550 nm	-5	-25

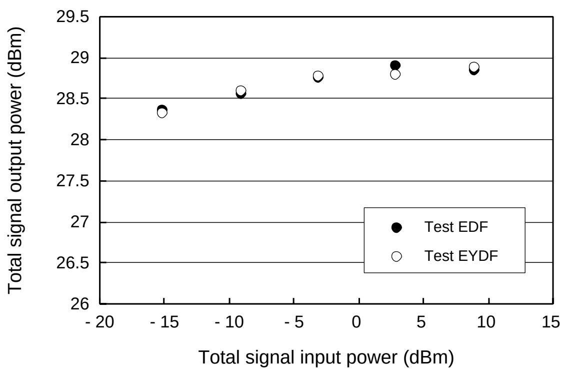

Figure 5 Signal input power dependence of output signal power

conversion efficiency (PCE) from pumping power to signal power. Thus measurements of the value of PCE may be taken as one indicator of whether conversion quenching is occurring or not.

The measurements were carried out using a single-stage amplifier configuration bi-directionally pumped at 1480-nm, at a signal wavelength of 1560 nm and a signal power of 0 dBm. Optimum length of EYDF was 7 m. PCE in the EYDF calculated from these results was 76% -- comparable to conventional EDF. Again it can be seen that there is no marked concentration quenching in this EYDF.

6. WDM SIGNAL AMPLIFICATION CHARACTERISTICS

Figure 4 shows a schematic diagram of the amplifier used to evaluate the WDM signal amplification characteristics, and Table 1 shows the characteristics of the fibers (EYDF and EDF) evaluated in this study.

The amplifier was of a two-stage configuration, pumped by wavelength-multiplexed 1480-mn laser diodes. The two-stage EDF / EYDF was pumped with a total launched power of 1.56 W from eight high-power 1480-nm laser diodes. Fiber lengths were 30 m (1st stage) and 51 m (2nd stage) for the EDF, and 4.5 m (1st stage) and 7 m (2nd stage) for the EYDF.

Using the configuration described above, 8-channel WDM signals with 2-nm spacing were applied and the nonlinear effects under high-power operating conditions were evaluated. Figure 5 is a graph plotting the signal input power dependence of output signal power. Maximum total output power reached 28.8 dBm (760 mW), or approximately 20 dBm per channel. This is an extremely high power characteristic to be achieved with only eight laser diodes, and was only made possible by making use of high-efficiency EDF, high-power diodes and highly efficient wavelength multiplexing technology.

Figures 6 and 7 show the output spectra of the EDF and EYDF, and a comparison of the two reveals a clear difference in the generation of nonlinear phenomena. Although clear evidence of four-wave mixing is apparent in the case of the EDF, virtually none shows in the EYDF spectrum. The total length of fiber used in the amplifier was 81 m for EDF and 11.5 m for EYDF, and this length difference had a major impact on the generation of FWM. That is to say, by raising the limitation on Er doping concentration through co-doping with Yb, it was possible to reduce effective length L_{eff} (or in other words to increase gain coefficient g), thereby suppressing nonlinearity below the level in the conventional EDF.

This demonstrates that EYDF has great possibilities as a fiber for high-power amplifiers that also provide low nonlinearity.

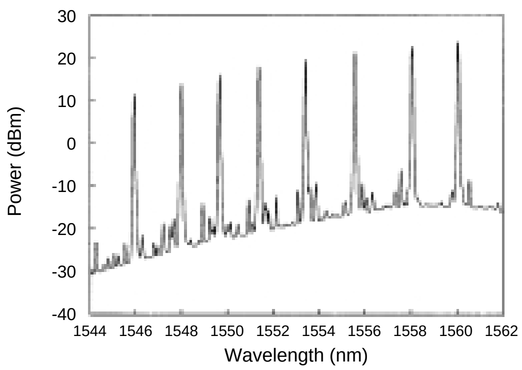

Figure 6 Output spectrum of EDF

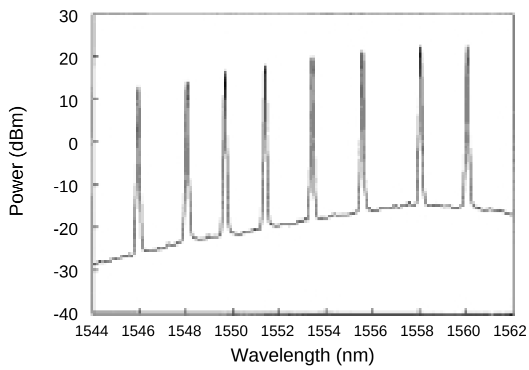

Figure 7 Output spectrum of EYDF

7. CONCLUSION

It has been found possible, by co-doping EDF with Yb, to inhibit the degradation in conversion efficiency associated with concentration quenching, while at the same time raising the limitation on Er doping concentration for conventional EDF. Use of the EYDF developed in the present work makes it possible to achieve a high-power amplifier that combines both low nonlinearity and high conversion efficiency--characteristics that have conventionally been in a trade-off relationship.

Studies are already under way on the possibility of applications to L-band, on optimization of core composition for even higher Er doping concentrations, and on lower nonlinearity, including amplifier fiber parameters.

REFERENCES

1) Y. Tashiro, S. Koyanagi, K. Aiso, K. Tanaka, S. Namiki, Furukawa Electric Review, No. 104, July 1999, p.59 (in Japanese)
2) T. Kimura, N. Tsukiji, A. Iketani, N. Kimura, H. Murata, Y. Ikegami, Optical Amplifiers and their Applications, (1999), ThD12.
3) K. Tanaka, K. Iwashita, Y. Tashiro, S. Namiki, and S. Ozawa, Optical Fiber Communication Conference, (1999), TuH5.
4) Y. Tashiro, S. Koyanagi, K. Aiso and S. Namiki, Optical Amplifiers and their Applications, (1998), WC-2.
5) G.R.Jacobovitz-Veselka, R. P. Espindola, C. Headley, A.J. Stentz, S. Kosinski, D. Inniss, D. Tipton, D. J. DiGiovanni, M. Andrejco, J. DeMarco, C. Soccolich, S. Cabot, N. Conti, J. J. Veselka, L. Gruner-Nielsen, T. Strasser, R. Pedrazzani, A. Hale, K. S. Kranz, R. G. Huff, G. Nykolak and P. Hansen, Optical Amplifiers and their Applications, (1997), PD-3.
6) S. G. Grubb, W. F. Humer, R. S. Cannon, T. H.Windhorn , S. W. Vendetta, K. L. Sweeney, P. A. Leilabady, W. L. Barnes, K. P. Jedrzejewski, and J. E. townsent, IEEE Photonics Technol. Lett., vol. 4, (1992), p. 553.
7) S.Grubb, D. J. DiGiovanni, J. R. Simpson, W. Y. Cheung, S. Sanders, D. F. Welch, B. Rockney, Optical Fiber Communication Conference, (1996), TuG4.
8) F. Di Pasquale, G. Grasso, F. Meli, G. Sacchi, S. Turolla, Optical Fiber Communication Conference, (1999), WA2.
9) J. M. Sousa, J. Nilsson, C. C. Renaud, J. A. Alvarez-Chavez, A. B. Grudinin, and J. D. Minelly, IEEE Photonics Technol. Lett., vol. 11, (1999), p39.
10) Y.Jaouen, J.-P.Bouzinac, J-M.P.Delavaux, C.Chabran and M.Le Flohic, Electron. Lett., vol. 36, no. 3, (2000), p.233.
11) M.Shtaif, M.Eiselt, R.W.Tkach, R.H.Stolen and A.H.Gnauck, Optical Amplifiers and their Applications, (1999), PD4.
12) S. Radic, G. Pendock, A. Srivastava, P. Wysocki and A. Chraplyvy, European Conference on Optical Communication, (1999), PD1-11.
13) M. Eiselt, M. Shtaif and R.W. Tkach, Optical Fiber Communication Conference, (1999), ThC1.
14) G.P.Agrawal, Nonlinear Fiber Optics 2nd edition, 1995 Academic Press Inc.
15) R. I. Laming, D. N. Payne, F. Meli, G. Grasso, E. J. Tarbox, Optical Amplifiers and their Applications, (1990), MB3.
16) S. Sudo, Editor, Optical fiber Amplifiers: Materials, Devices, and Applications, Artech House, Inc., Boston, (1997), p. 174.
17) K. Arai, H. Namikawa, K. Kumata and T. Honda, J. Appl. Phys., vol. 59, (1986), p. 3430.
18) P. Myslinski, D. Nguyen and J. Chrostowski, J. of Lightwave Tech., vol. 15, no. 1, (1997), p. 112.
19) N. Sugimoto, Y. Kuroiwa, K. Ochiai, S. Ohara, Y. Fukasawa, S. Ito, Optical Amplifiers and their Applications, (2000), PD-3.
20) M. Federighi, and F. Di Pasquale, IEEE Photonics Technol. Lett., vol. 7, (1995), p. 303.
21) W. L. Barnes, S. B. Poole, J. E. Townsend, L. Reekie, D. J. Taylor, and D. N. Payne, J. of Lightwave Tech., vol. 7, no. 10, (1989), p. 1461.
22) Y. Tashiro, K. Mori, T. Izumikawa, H. Nimura, K. Aiso,T. Yagi, S. Namiki, Proc. Optical Amplifiers and their Applications, (2000), OtuA3.

Manuscript received on November 2, 2000.