Wideband Hybrid Fiber Amplifier Using Er-Doped Fiber and Raman Medium

Hong-Seok Seo , Joon Tae Ahn, Bong Je Park, and Woon Jin Chung

In this paper, we report the experimental results of a hybrid wideband fiber amplifier. The amplifying medium is a concatenated hybrid fiber consisting of Er-doped fiber (EDF) and dispersion compensating fiber (DCF). The gain mechanisms are based on stimulated emission in the EDF and stimulated Raman scattering (SRS) in the DCF. Since we simultaneously use optical amplification by the two processes, the gain bandwidth is easily expanded over 105 nm by a two-tone pumping scheme. Using an experimental setup constructed with a hybrid structure of EDF-DCF-EDF, we analyzed the spectral behavior of amplified spontaneous emission for pumping powers. We achieved an optical gain of over 20 dB in the wavelength range from 1,500 to 1,600 nm under optimized pumping conditions to make the spectral gain shape flat.

Keywords: WDM, Ge, Er, SRS, Raman amplifier, EDF, DCF, S band, C band, L band, fiber amplifier, wideband, hybrid type.

I. Introduction

Wideband fiber amplifiers have been continuously researched and developed to increase the transmission capacity of wavelength division multiplexing optical communication systems [1]-[11]. The key mechanism of a fiber amplifier is mainly based on the stimulated radiative transition of rare earth ions or on stimulated Raman scattering (SRS) in the fiber core doped with a nonlinear material. Sun and others first constructed a wideband erbium doped fiber amplifier (EDFA) covering the C and L bands [3], but there is a seam between the gain bands where optical signals are distorted by interference and amplified poorly. Ono and others constructed an S-band EDFA with a band rejection filter in C band [4]. The S-band EDFA was further developed through a depressed-cladding silica-based Er-doped fiber (EDF) based on fundamental mode cutoff instead of a C-band rejection filter [5], [6]. This result is significant because the S+C+L band fiber amplifier can be directly realized or systemized with only EDF if the seams existing between gain bands are not crucial [7].

Raman amplifiers have also attracted considerable attention due to their amazing bandwidth expansion over 100 nm with the development of high power semiconductor laser diodes. However, since the Raman-gain spectrum is not inherently flat and the gain band width is fixed at around 20 nm under a single wavelength pumping scheme, multi-wavelength pumping techniques have generally been used to achieve bandwidth expansion and gain flattening. Thus, many optical devices were required for wideband optical amplification [1], [8]. Masuda and others reported a hybrid fiber amplifier showing wide and seamless bandwidth with high gain in the C and L bands [8]. They also used multiple pumping sources with different wavelengths to separately pump EDF and Raman fiber.

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Akasaka also reported a two-stage hybrid amplifier covering S+C+L bands consisting of a distributed Raman amplifier and a fluoride-based EDFA [9]. The first stage is a distributed type Raman amplifier pumped by two pumping sources at 1,410 and 1,495 nm. The second stage is an erbium-doped fluoride fiber amplifier pumped by a 980 nm laser diode. In this case, the C-band signals passing through a 50 km distributed Raman fiber can experience optical loss, which makes a high NF in the C band.

Recently, we proposed a new amplification scheme which simultaneously uses direct transitions of Er ions and SRS in an Er-doped Raman fiber [10], [11]. We demonstrated through simulation that wideband amplification over 100 nm is achievable using a hybrid structure composed of EDF and dispersion compensating fiber (DCF) in two-tone pumping schemes [11].

In this paper, with a hybrid fiber consisting of EDF and DCF, we experimentally demonstrate a wide-band amplifier showing a seamless gain characteristic in bands of 1,500 to 1,600 nm using pumping sources with two different wavelengths. Compared to fiber Raman amplifiers with similar gain and bandwidth [1], this hybrid erbium/Raman fiber amplifier requires a lower number of optical devices due to the two-tone pumping scheme and low total pumping power due to better pump power conversion efficiency of EDF compared to that of Raman fiber for C band. These advantages can be expected to result in cost effectiveness as well as good performance.

II. Analysis

Figure 1 shows the basic principle of wideband amplification in the hybrid Er/Raman fiber amplifier. The black line represents a typical Raman gain spectrum of a high Ge-doped silica fiber (DCF) pumped by two pumping sources operating at 1,411 and 1,490 nm, respectively. The two Raman gain peaks appeared at the wavelengths of 1,505 and 1,590 nm which were down-shifted about 100 nm from the pumping wavelengths. The red line shows a typical gain curve of an EDFA. These two graphs seem to be the reverse of each other. The Raman gain dramatically decreases in the wavelength range of 1,520 to 1,530 nm. It then monotonically increases for the wavelengths of 1,565 to 1,590 nm. However, the gain shape of EDFA rapidly grows in the range from 1,520 to 1,530 nm and then slowly reduces between 1,565 and 1,590 nm. If we mathematically add the two gain graphs, it is predictable that a wideband flat gain spectrum can be easily synthesized in the spectral domain as shown in the green line. Therefore, seamless-wideband amplification can be easily achieved using the proposed fiber amplifier with a simple pumping scheme, although gain valleys appear in the range from 1,520 nm to 1,570 nm.

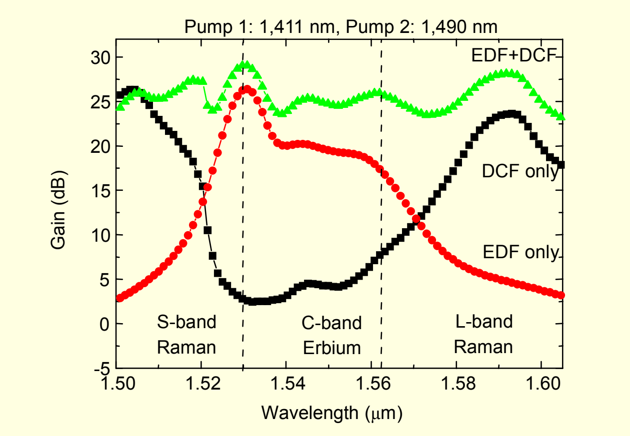

Fig. 1. Basic principle of wideband amplification in the hybrid Er/Raman fiber amplifier. The black line is from DCF pumped at 1,411 and 1,490 nm. The red line is the gain from a typical EDFA. The green line is a simulation result obtained simultaneously from the EDF and DCF.

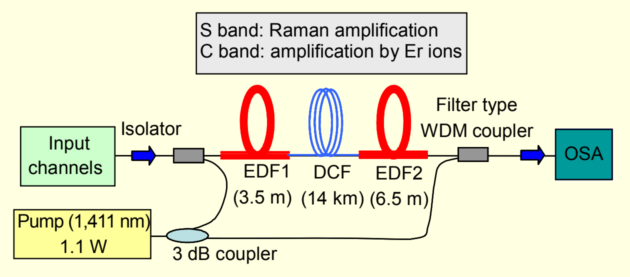

Fig. 2. Experimental setup for the S+C band Er/Raman fiber amplifier.

III. Experiments

1. Hybrid Fiber Amplifier for S+C Band

Figure 2 shows an experimental setup for the S+C band Er/Raman fiber amplifier. We employed hybrid optical fibers composed of EDF1 (3.5 m) on the input side, DCF (14 km), and EDF2 (6.5 m) on the output side. These were spliced in a series as an active medium. The absorption coefficient of the EDFs was about 10 dB/m and the Raman gain coefficient and loss of the DCF were 2.6/(W·km) and 0.58 dB/km, respectively. The power of the pump laser was evenly divided by a 3 dB coupler and then fed forward and back into the active fibers through two filter type WDM couplers at the input side and output side, respectively. The pump laser has a single wavelength line of 1,411 nm with the maximum available power of 3 W. This wavelength was selected to provide optical amplification via optimization of the spectral gain overlap between the S and C bands. The lengths of EDF1 and

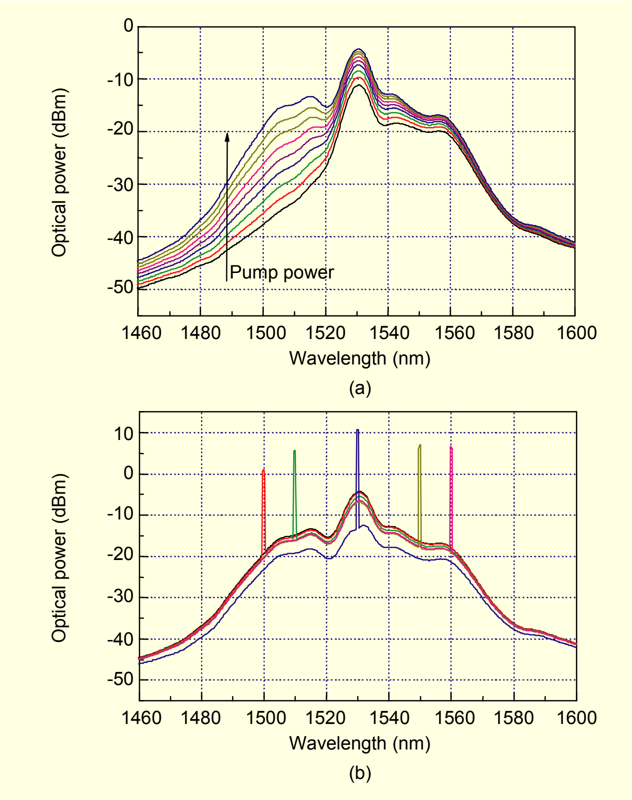

Fig. 3. (a) ASE behavior in relation to pumping power and (b) small signal amplification at pumping power of 1.1 W.

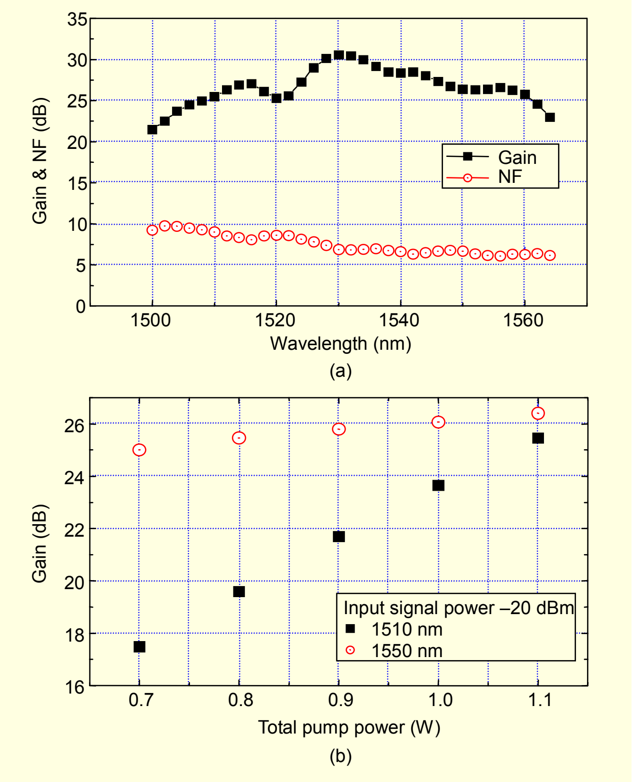

Fig. 4. (a) Gain and NF for input signal of -20 dBm at the pumping power of 1.1 W and (b) gain variations in relation to pumping power.

EDF2 were experimentally determined by considering the gain and noise figure (NF) in the C band. It is well known that the EDF1 of the input side strongly affects the NF of the C band. Without it, the C-band signals experience an optical loss when they are passing through the DCF, which is directly reflected in the NF. If it is too long, the NF at the S band increases because Er ions absorb the corresponding signals. The EDF2 further boosts the C-band signals to make an optical gain corresponding to the gain level of the S-band achievable from the DCF (14 km) by Raman. The principle for wideband amplification is as follows. First, the C band amplification is performed by the EDFs which are excited into a high energy level by absorption of the pump energy, despite the inherently low absorption of erbium ions at 1,411 nm. The S band amplification occurs in the DCF through SRS induced by the remaining pump power which is not absorbed by the EDFs, resulting in a Raman gain peak at 1,510 nm.

Figure 3(a) exhibits amplified spontaneous emission (ASE) characteristics according to a pumping power increase of 0.1 W from 0.3 to 1.1 W. Clearly, S-band ASEs in the wavelength range between 1,500 and 1,530 nm were strongly re-amplified by the pump power remaining after Er ions in the EDFA were almost excited by the pump energy. Note that the ASE shape in the S-band range was formed by combination of ASE in the EDF and ASE by SRS in the DCF. Likewise, the C-band ASE from 1,530 to 1,560 nm was due to the EDF's ASE with the aid of SRS in small quantity. When the pump power reaches 1.1 W, the flat ASE behavior in the S- and C-band range was observed without any gain equalizing filter. With a fixed pumping power of 1.1 W, we fed an input signal of -20 dBm into the amplifying system. Figure 3(b) shows the results measured individually for 5 selected wavelengths displayed simultaneously. For all measured wavelengths, the signal gain was over 20 dB. Near the wavelength of 1,530 nm, the gain reached 30 dB.

Figure 4(a) shows the gain level and NF for the input signal power of -20 dBm. The pumping power was about 1.1. Under these conditions, the average gain value was approximately 26 dB with the NF between 6.0 and 10.0 dB. The S-band gain started to increase at the wavelength of 1,500 nm and showed a peak at 1,515 nm. The gain shape due to Er ions in the C band was further enhanced by SRS induced by the pump and was slightly different from that of a typical EDFA. The NF in the S-band range was high, at about 8 to 10 dB, due to optical loss in the EDF1 (3.5 m). Figure 4(b) shows gain variations for the pumping power at the wavelengths of 1,510 nm (black) and 1,550 nm (red). The S-band gain variation by Raman was more sensitive to the pumping power than the C band gain variation by EDF.

2. Hybrid Fiber Amplifier for S+C+L Band

Figure 5 depicts an experimental setup for amplification in the range from 1,500 to 1,600 nm using EDF1 (1.5 m), DCF (14 km), and EDF2 (3 m). To pump the hybrid media bidirectionally, the pump laser (P1) provides optical amplification for the S and C bands as shown in Fig 2. The low-power pump laser diode (P2), having a wavelength of 1,490 nm, was newly added as a backward pumping source to supplement optical amplification by minimizing the gain overlap between the C and L bands. Since the energy of P1 is easily transferred to P2 by Raman interaction, the power of P2 should be moderately controlled for spectral gain flattening. The lengths of EDF1 and EDF2 were experimentally determined to be 1.5 m and 3 m in the same way.

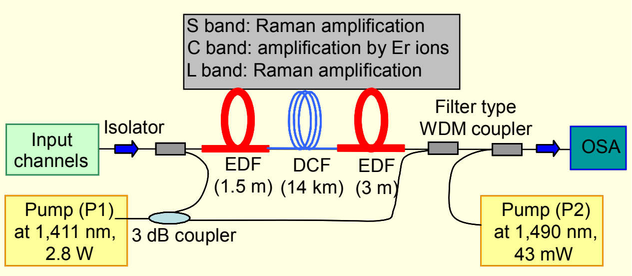

Fig. 5. Experimental setup for the S+C+L band Er/Raman fiber amplifier.

Figure 6(a) shows the ASE characteristics according to a power increase from 0.8 to 2.8 W for P1 in increments of 0.4 W. With the power variation of P1, we reversely decreased the power of P2 from 153.7 to 42.7 mW for ASE flattening from the S to L band because the power of P2 was gradually boosted by P1 due to Raman interaction. In these graphs, the C-band amplification was first performed by Er ions in EDF which were excited into a high energy level by absorption of P1 and P2. The growth rate was saturated step by step for the increase of the power of P1 because the length of the EDFs was fixed. Then the S- and L-band amplification was caused by SRS in the DCF with the aid of the remaining pump power of P1 and P2 and was proportionally enhanced with the pump powers. When the pump powers of P1 and P2 reached 2.8 W and 42.7 mW, respectively (solid line), flat ASE behavior in the S+C+L band range was observed without any gain equalizing filter. Although the gain valleys at the wavelengths of 1,520 and 1,570 nm still exist as predicted in Fig. 1, the variations were smoother than those shown Fig. 2. Under these conditions, we fed an input signal with a power of -20 dBm into the amplifying system. Figure 6(b) shows the results measured individually for 5 selected wavelengths displayed simultaneously. For all measured wavelengths, the signal gain was over 20 dB.

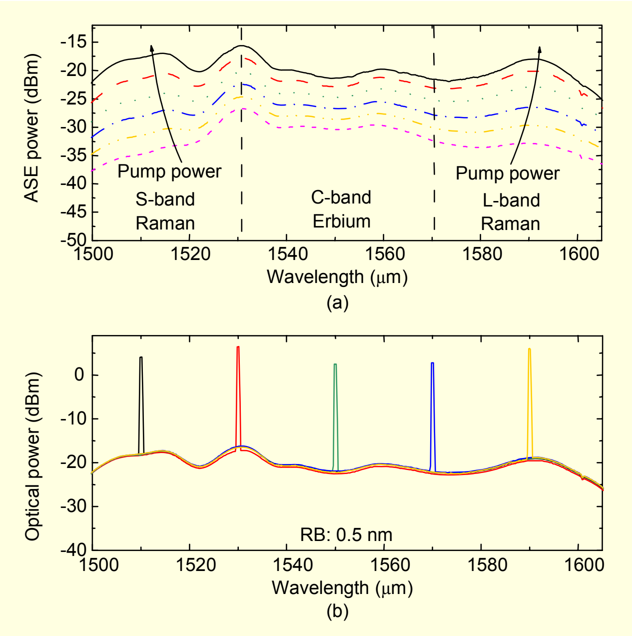

Fig. 6. (a) ASE behavior in relation to pumping power and (b) small signal amplification from pumping sources of P1 (2.8 W) and P2 (42.7 mW).

Figure 7 exhibits the resultant gains and NFs obtained at the pump powers of 2.8 W (P1) and 42.7 mW (P2). The black and red lines are gains and NFs for small input signals of -20 dBm and -25 dBm, respectively. The S-band gain started to increase at the wavelength of 1,500 nm and showed peaks at 1,512 nm by SRS from P1. The typical gain peak at 1,530 nm by Er ions was further enhanced by SRS induced by the energy of P1 and P2. The L-band gain peak appeared at the wavelength range of 1,592 nm by SRS from P2. The magnitudes of these main peaks at 1,512, 1,530, and 1,590 nm are closely related. The

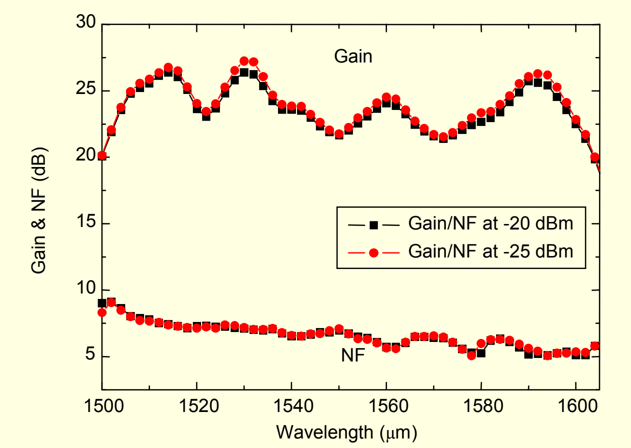

Fig. 7. Gains and NFs at P1 (2.8 W) and P2 (42.7 mW). The black and red curves marked are gains and NFs for small input signals of -20 dBm and -25 dBm, respectively.

overall gain from 1,500 to 1,600 nm reached over 20 dB irrespective of the signal powers of -20 and -25 dBm. For the high signal power over -15 dBm, the amplifier showed a temporal instability at the L band, which was so-called stimulated Brillouin scattering. However, it could be easily removed by adding an amplitude or phase modulating device in the input signal port. The NFs from the S band to the L band slightly decreased from 9 to 5 dB without regard to the signal power in the wavelength domain. The high NF in the S-band range can be further improved by the optimum combination of EDFs and DCFs or by changing the amplifying structure shown in Figs. 2 and 5 into a two-stage system with improved pumping schemes. The overall spectral shapes of gain and NF were similar to the simulation results shown in Fig. 4 of [11] because the configuration of forwardly pumped EDF-DCF in the prior work was not very different from this experimental setup except for the pumping schemes and the arrangement of the hybrid fibers.

IV. Conclusion

We have experimentally demonstrated that wideband optical signals in a range from 1,500 nm to 1,600 nm can be amplified seamlessly and simultaneously through a combined medium of EDF and DCF by a simple pumping scheme. The overall gain was over 20 dB and the variation was lower than 5 dB in all the bands. This hybrid Er/Raman fiber amplifying system is expected to be cost effective and to perform well. It requires a reduced number of WDM devices to combine pump sources and requires lower total pump power because of the better pump power efficiency of EDF than that of Raman fiber for C band. As a future work, analysis and experiments for double Rayleigh back scattering will be pursued to improve the hybrid amplifier's performance.

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V. References

[1] H. Kidorf, K. Rottwitt, M. Nissov, M. Ma, and E. Rabarijaona, "Pump Interactions in a 100-nm Bandwidth Raman Amplifier," *IEEE Photon. Technol. Lett.*, vol. 11, no. 5, May 1999, pp. 530-532.

[2] W.J. Chung, H.S. Seo, B.J. Park, J.T. Ahn, and Y.G. Choi, "Selenide Glass Optical Fiber Doped with Pr^{3+} for U-Band Optical Amplifier." *ETRI Journal*, vol. 27, no. 4, Aug. 2005, pp.411-417.

[3] Y. Sun, J.W. Sulhoff, A.K. Srivastava, J.L. Zyskind, T.A. Strasser, J.R. Pedrazzani, C. Wolf, J. Zhou, J.B. Judkins, R.P. Espindola, and A.M. Vengsarkar, "80-nm Ultra-wideband Erbium-Doped Silica Fiber Amplifier," *Electron. Lett.*, vol. 33, no. 23, Nov. 1997, pp. 1965-1966.

[4] H. Ono, A. Yamada, and M. Shimizu, "S-Band Erbium-Doped Silica Fiber Amplifier with Flattened-Gain of Over 21 dB," *Electron. Lett.*, vol. 38, no. 19, Sept. 2002, pp. 1084-1086.

[5] M.A. Arbore, Y. Zhou, G. Keaton and T. Kane, "34 dB Gain at 1500 nm in S-Band EDFA with Distributed ASE Suppression," *Proc. ECOC*, 2002, paper 2.2.2.

[6] F. Poli, M. Foroni, A. Cucinotta, S. Selleri, and P. Vavassori, "Single-Stage S-band Depressed Cladding EDFA with Bending Loss ASE Suppression," *Proc. ECOC'*05, 2005, paper Th 3.3.6.

[7] C.H. Yeh, C.C. Lee, and S. Chi, "120-nm Bandwidth Erbium-Doped Fiber Amplifier in Parallel Configuration," *IEEE Photon. Technol. Lett*. vol. 16, no. 7, July 2004, pp.1637-1639.

[8] H. Masuda and S. Kawai, "Wideband and Gain-Flattened Hybrid Fiber Amplifier Consisting of an EDFA and a Multi-wavelength Pumped Raman Amplifier," *IEEE Photon. Technol. Lett*, vol. 11, no. 6, June 1999, pp. 647-649.

[9] Y. Akasaka, "Gain Bandwidth of Optical Amplifiers Over 100 nm and Beyond," *Proc. ECOC*, 2003, paper Tu 3.7.1.

[10] H.S. Seo, W.J. Chung, and J.T. Ahn, "S Plus C Bands Amplification in a Distributed E-Doped Raman Fiber," *IEEE Photon. Technol. Lett.*, vol. 17, no. 6, June 2005, pp. 1181-1183.

[11] H.S. Seo, W.J. Chung, and J.T. Ahn, "A Novel Hybrid Silica Wideband Amplifier Covering S+C+L Bands with 105-nm Bandwidth," *IEEE Photon. Technol. Lett.*, vol. 17, no. 9, Sept. 2005, pp. 1830-1832.

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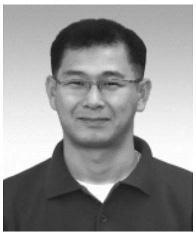

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