Performances of Erbium-Doped Fiber Amplifier Using 1530nm-Band Pump for Long Wavelength Multichannel Amplification

Bo-Hun Choi , Moo-Jung Chu, Hyo-Hoon Park, and Jong-Hyun Lee

The performance of a long wavelength-band erbium-doped fiber amplifier (L-band EDFA) using 1530nm-band pumping has been studied. A 1530nm-band pump source is built using a tunable light source and two C-band EDFAs in cascaded configuration, which is able to deliver a maximum output power of 23dBm. Gain coefficient and noise figure (NF) of the L-band EDFA are measured for pump wavelengths between 1530nm and 1560nm. The gain coefficient with a 1545nm pump is more than twice as large as with a 1480nm pump. It indicates that the L-band EDFA consumes low power. The noise figure of 1530nm pump is 6.36dB at worst, which is 0.75dB higher than that of 1480nm pumped EDFA. The optimum pump wavelength range to obtain high gain and low NF in the 1530nm band appears to be between 1530nm and 1540nm.

Gain spectra as a function of a pump wavelength have bandwidth of more than 10nm so that a broadband pump source can be used as 1530nm-band pump. The L-band EDFA is also tested for WDM signals. Flat Gain bandwidth is 32nm from 1571.5 to 1603.5nm within 1dB excursion at input signal of –10dBm/ch. These results demonstrate that 1530nm-band pump can be used as a new efficient pump source for L-band EDFAs.

I. INTRODUCTION

Long wavelength-band erbium-doped fiber amplifier (L-band EDFA) has been rapidly developed following the conventional 1550nm band (C-band) EDFA as a component for wideband wavelength division multiplexing (WDM) transmission systems [1]-[4]. Although the gain region of EDFA is larger than 100nm, EDFA using only about 30nm bandwidth in C-band was developed in first several years. With enhancement of EDF manufacturing technology and need of optical bandwidth increment in optical communications, EDFA for L-band with another 30nm bandwidth between 1570nm and 1600nm has been developed [5], [6].

One of the major merits of the L-band EDFA is that it expands the optical bandwidth when used in parallel with the C-band EDFA [7]. Another merit is that L-band transmission in dispersion-shifted fiber does not have four wave mixing problem [8]. Moreover, the EDFA can easily achieve flat gain without a gain-flattening filter compared with the C-band EDFA [9], [10].

There have been various efforts to improve the amplification characteristics of the L-band EDFA, in which the main issue is the selections of a proper pump wavelength and pumping configuration [6],[11],[12]. Amplified spontaneous emission (ASE) of C-band EDFA has been used as the injection seed source for L-band EDFA [13]. The pump wavelength dependence of the amplification characteristics of EDFA has been reported mainly in 800, 980, and 1480nm bands, and now 980 and 1480m bands are mostly used for L-band EDFAs [14]-[16]. On the other hand, 1555nm wavelength had been examined as

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a pump wavelength but it was reported that noise figures (NFs) were detrimental and gain did not have merits [17],[18]. A 1555nm distributed feedback laser diode(LD) had also been investigated as a subsidiary pump with 980 and 1480nm band pumping to suppress backward ASE at the input end of erbium-doped fiber and there was a 20% improvement of gain coefficient [19].

We use 1530nm band as new pump wavelength for the L-band EDFA. Gain coefficient, power conversion efficiency (PCE), and NF are measured as the pump wavelength is varied from 1530nm to 1560nm with a 3nm interval to determine pumping efficiency. Those of 1480nm-pumped L-band EDFA are also measured to compare with the results of 1530nm-band pumped L-band EDFA. The reason for variations of pumping efficiency with pump wavelength is analyzed in terms of powers of forward ASE. The gain spectra as functions of the pump wavelength and power are investigated to see bandwidth of pump wavelength. Finally, the gain of WDM signals was measured to investigate flat gain bandwidth for WDM transmission systems, in which WDM signals of 5 channels were emulated with a probe signal and a saturating signal.

II. EXPERIMENTS

1. Experimental Setup

The experimental setup is shown in Fig. 1. We used a 65m-long silica-based EDF (Fibercore co., England) which has a cutoff wavelength of 1330m and a numerical aperture of 0.22. It is doped with Er^{3+} ions to a level corresponding to absorption of 7.6 dB/m and 2.85dB/m at the 1530nm absorption peak and 1480nm pump absorption region respectively. The EDF length for L-band amplification was limited by available pumping power. A forward pumping scheme was used in this experiment to utilize an advantage of 1530nm-band pumping. A tunable light source (TLS) provided a probe signal between 1560nm and 1630nm and the output was detected with an optical spectrum analyzer (OSA). The TLS and the OSA were controlled automatically by a computer via a GP-IB interface.

2. 1530nm-Band Pumping Source and WDM Coupler

Our 1530nm-band pump source was composed of a TLS and two C-band EDFAs in cascaded configuration as shown in Fig. 1. The EDF on the first EDFA was 10m long and pumped by 980nm LD in forward direction, and the EDF on the second EDFA was 20m long and pumped by two 1480nm LDs bidirectionally. The cascaded EDFA was designed to have high output power of 23dBm. Pump wavelength for examined 65m-long EDF was determined by controlling TLS. Light from the TLS was amplified by a cascaded EDFA and launched into EDF through an optical tunable filter (OTF) suppressing the ASE noise of the cascaded EDFA. The OTF (OTF-300-06S, Santec co., Japan) had 2.6dB insertion loss including the loss in connectors and it had 20dB-bandwidth of 7nm.

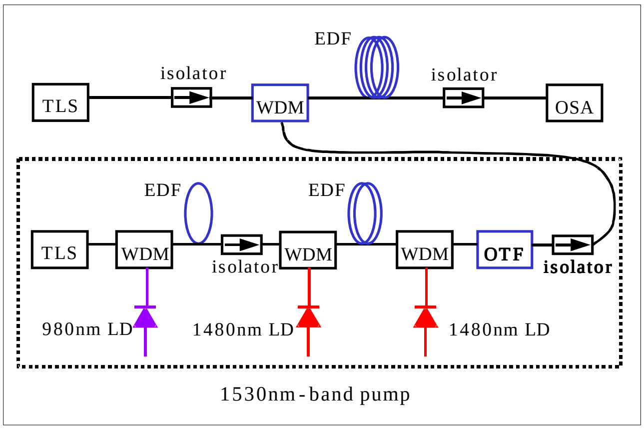

Fig.1. Experimental configuration of 1530nm-band pumped L-band EDFA. TLS: tunable light source; WDM: wavelength-division multiplexer; EDF: erbium-doped fiber; OTF: optical tunable filter.

Figure 2 shows the spectra of 1530nm-band pumps having wavelengths of 1530, 1545 and 1560nm, and output powers of 30mW, 50mW, and 70mW. Side mode suppression ratio (SMSR) of each pump is almost 60dB. This good SMSR could be achieved because the TLS of about 45dB SMSR was filtered through the OTF. The spectra show that ASE power level of the pump is low enough not to affect the L-band EDFA regardless of pump power and wavelength.

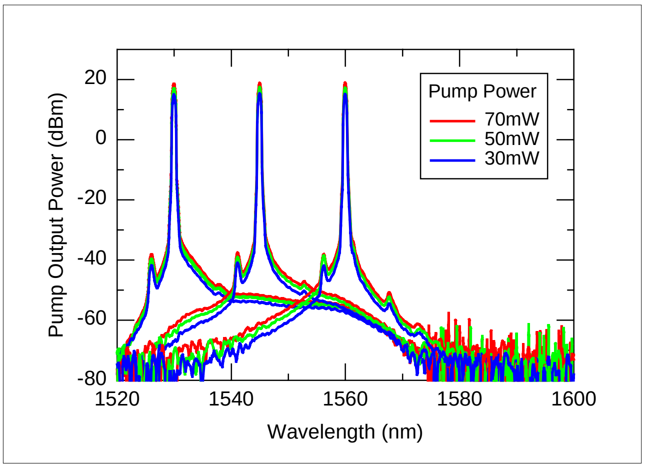

Fig.2. The spectra of 1530nm-band pumps with pump wavelengths of 1530, 1545 and 1560nm at pump powers of 30mW, 50mW, and 70mW.

An L-band signal and a 1530nm-band pump were multiplexed by a WDM coupler (E-tek Inc., USA). The measured insertion loss spectrum of the WDM coupler is shown in Fig. 3. The pump band and signal band are divided at around 1565nm.

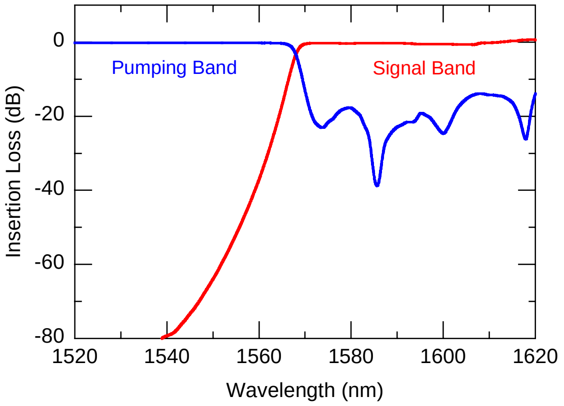

Fig.3. The insertion loss spectra of a WDM coupler multiplexing an L-band signal and a 1530nm-band pumping source.

If the two bands are divided at a shorter wavelength than 1560nm, the ASE noise of the pump can be suppressed by the WDM without the OTF and the structure of the pump can be simplified. Pump ASE noise of around 1560nm seriously degraded amplification characteristics of the L-band EDFA if it was not removed.

III. RESULTS

1. Comparison of the Amplification Characteristics of 1530nm Band and 1480nm Pumped L-Band EDFA

To investigate the pump wavelength dependence of the amplification characteristics of the L-band EDFA, gain and noise figure (NF) were measured varying the pump wavelength from 1530nm to 1560nm with a 3nm interval. Figure 4(a) shows gain spectra of 1533nm pumped L-band EDFA. Signal wavelength range is from 1569.5 to 1621.5nm with a 2nm interval and power is –30dBm. The pump power is varied from 30mW to 70mW. As the pump power increases, population inversion changes and the gain around 1570nm becomes greater than around 1600nm. At 42mW pump power, gain spectrum is flattened between 1571.5nm and 1601.5nm within 1nm excursion. Figure 4(b) shows NF spectra on the same condition of Fig. 4(a). There is no remarkable difference on the NF spectra with the variation of pump power. The worst value of NF in the flat gain region is 6.55dB obtained at 1571.5nm for 42mW pump power. The degradation of the NF at wavelengths near 1570nm and longer than 1600nm is known to arise due to the ground state absorption and the signal excited state absorption of Er^{3+} ions, respectively [5], [6].

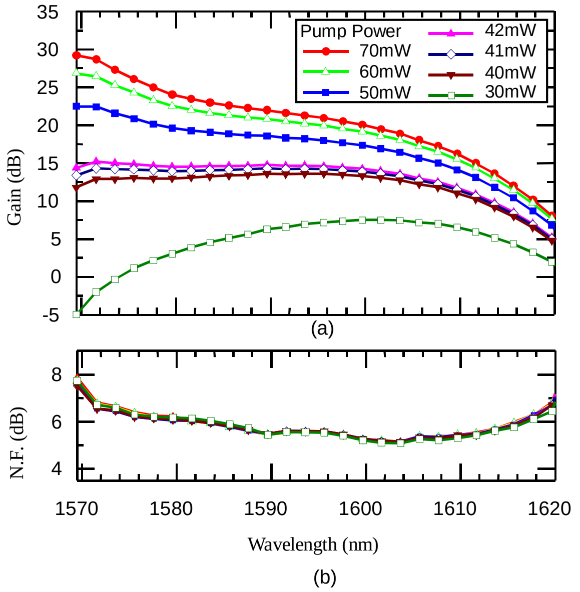

Fig.4. (a) Gain spectra and (b) noise figure spectra of 1533nm pumped L-band EDFA for pump powers from 30mW to 70mW.

Figure 5 shows measured data of relative power conversion efficiency (PCE) and gain coefficient with the variation of pump wavelength in the L-band EDFA. We compared the data with those obtained from a conventional 1480nm pumped L-band EDFA. PCE is given by the following equation:

$$PCE = (P_{sigout} - P_{sigin}) / P_{pump}$$

where P_{sigout}, P_{sigin} and P_{pump} are the signal output power, the signal input power and the pump power, respectively. The relative PCE was defined as the ratio of PCE of the 1530nm-band pumped EDFA to that of the 1480nm pumped EDFA. The gain coefficient was attained from the ratio of signal gain to applied pump power and could be used as the index of pump power because equal gains were required in this experiment. The gain and NF measurements were repeated as the pump wavelength was varied from 1530nm to 1560nm with a 3nm interval. For these pump wavelengths compared are the pump powers required for 15dB flattened gain with less than 1dB excursion between 1571.5 and 1601.5nm. Input signal power was –30dBm at each signal wavelength. For the experimental setup of the 1480nm pumped EDFA, 1530nm-band pump source was replaced by a 1480nm semiconductor LD. Otherwise, the setup remained the same Fig. 1. The gain coefficient of the1480nm pump shown in Fig. 5 is 0.2dB/mW that is consistent with the value reported in similar experiment [11]. The gain coefficient and the relative PCE with 1545nm pumping in 1530nm band are 0.45dB/mW and 2.25, respectively. These values are more than twice as large as those of the 1480nm pump. The high gain coefficient indicates that the L-band EDFA consumes low optical pump power and low electrical power.

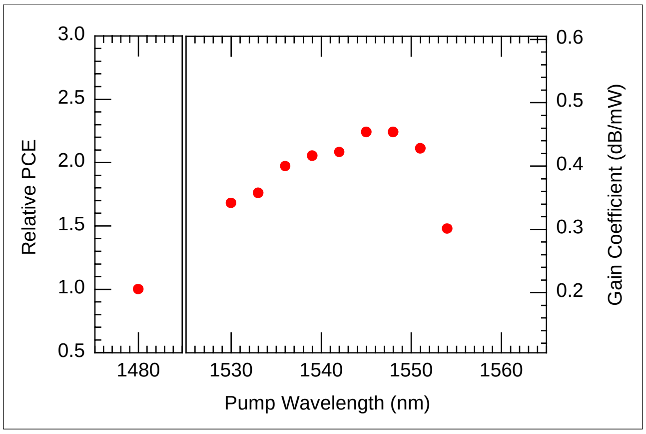

Fig.5. Relative power conversion efficiency (PCE) and gain coefficient of the L-band EDFA with variation of pump wavelength in 1530nm band and at 1480nm. The pump power was adjusted for a 15dB flattened gain level.

NFs shown in Fig. 6 correspond to the data shown in Fig. 5. NFs are 6.36dB with 1530nm pump and 6.55 dB with 1533nm pump at the signal wavelength of 1571.5 nm, where NF has the worst value in our measurement range. The NFs with these pump wavelengths are increased by less than 1dB compared with those with the 1480nm pump. This is not so serious considering the advantages in gain improvement. However, NF is degraded as the pump wavelength becomes longer.

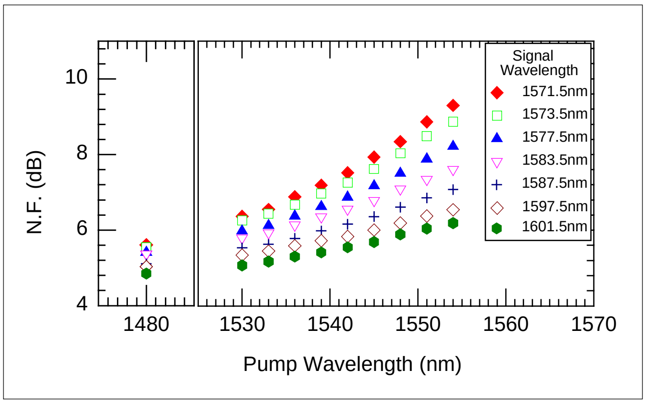

Fig.6. Noise figure of the L-band EDFA with variation of pump wavelength in 1530nm band and at 1480nm.

PCEs, gain coefficients and NFs could not be measured in the case of pump wavelength of 1557nm and 1560nm, because gain coefficients were too low to be detected in our experimental range and 15dB flattened gain spectra were not possible to be obtained.

The main reason of gain coefficient increment in 1530nm-band pumping is that the backward ASE is suppressed at the input end of EDF owing to the 1530nm-band pump, so that the pump power could be converted more efficiently to the signal power [18], [19]. However, the gain coefficient decreases for the pump wavelengths longer than 1550nm, because the absorption of the pump power becomes low. This will be confirmed in Figs. 7 and 8. The NF increases rapidly as the pump wavelength becomes longer, especially close to 1560nm, because ground state absorption also increases [5], [6].

Figure 7 shows forward ASE spectra for different pump wavelengths with the launched pump power of (a) 70mW and (b) 30mW. The narrow peak in the spectra is pump power that is not absorbed. The pump power is well absorbed with 1530nm pumping. But the longer the pump wavelength is, the less pump power is absorbed and the more the slope of ASE spectrum is smoothed. The trend of gain coefficient increment in a short pump wavelength region below 1545nm shown in Fig. 5 can be confirmed in Fig. 7(b) because the pump powers used to obtain the gain coefficients are close to 30mW. Likewise, the trend of gain coefficient decrease in a long pump wavelength above 1550nm shown in Fig. 5 can be understood in Fig. 7(a) because the pump powers used to obtain the gain coefficients are close to 70mW.

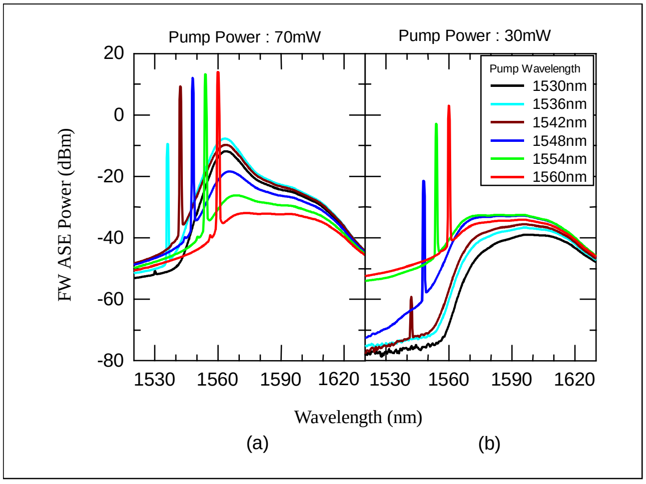

Fig.7. ASE spectra for various pump wavelengths with the pump powers of (a) 70mW and (b) 30mW.

In Fig. 7(a), although the same pump powers are applied, the slope of ASE spectrum curves becomes smooth as pump wavelength becomes longer. When the pump wavelength approaches 1560nm, there is no ASE spectrum required for a 15dB flattened gain spectrum. These results agree well with the tendency that the gain coefficient decreases in a longer pump wavelength than 1550nm shown in Fig. 5. On the contrary, it is clearly shown in Fig. 7(b) that the launched pump power is well absorbed in a pump wavelength below 1545 nm, because the pump power which is not absorbed and remains in the ASE spectrum is low.

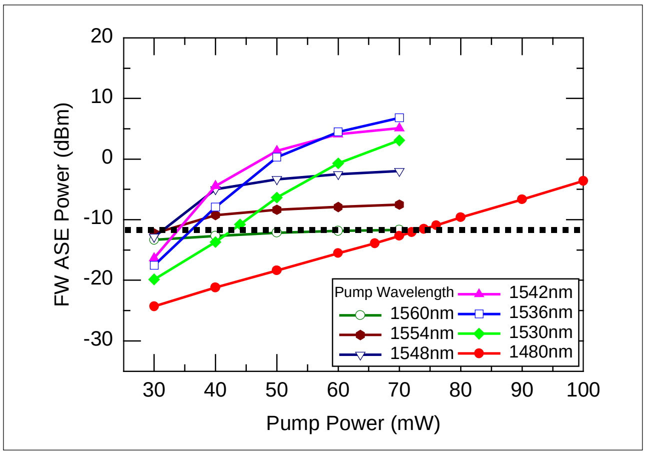

Fig.8. Forward ASE powers as a function of pump power in 1530nm-band pumped L-band EDFA.

Figure 8 shows forward ASE powers as a function of a pump power. Forward ASE powers were determined from the forward ASE spectra shown in Fig. 7, where the remaining pump powers were excluded. The forward ASE power increases in direct proportion to the launched pump power at 1480nm pump, whereas saturations appear with 1530m-band pumping. It is clear from Fig. 7 that the saturation of forward ASE power is due to pump power which passes through EDF without absorption. As the pump wavelength becomes longer, the saturation appears more clearly and moves to lower pump power, and the forward ASE power becomes smaller. Furthermore, in 1560nm pumping 15dB flattened gain cannot be obtained within available pump power. A dotted horizontal line in Fig. 8 shows powers of ASE spectra required for 15dB flattened gain for each curve. It means that there is the power level which is needed for 15dB flattened gain in this pump configuration. But in the case of 1560nm pump wavelength curve, there is no crossing point with the dotted line so the gain coefficient could not be attained in Fig. 5. Complete saturation in this curve indicates that it is difficult to get 15dB flattened gain in the longer pump wavelength than 1560nm although the pump power is sufficiently great.

Figure 9 shows the gain versus pump wavelength for various pump powers and signal wavelengths of (a) 1571.5nm, (b) 1581.5nm, (c) 1591.5nm, and (d) 1601.5nm, respectively. For the same pump power, gain profiles are different from (a) to (d) because the emission cross section is a function of signal wavelength. Population inversion depends on the pump power so that the gain of longer signal wavelength is relatively larger at low pump power and gain of shorter signal wavelength is larger at high pump power. Gain profiles for each signal wavelength also show similar trends that pump wavelength to obtain the highest gain moves to shorter pump wavelength as pump power increases, and slope of gain profile is steep on the longer pump wavelength side. This steepness is due to low absorption of pump power as explained in Figs. 7 and 8. Considering these results together with those of gain coefficient and NF, a wavelength between 1530nm and 1540nm is recommended as pump wavelength in the 1530nm-band for high gain and low NF. Additionally another important thing comes from the fact that 3dB bandwidth of the gain spectra is more than 10nm. It means that broadband source, as well as single wavelength source can be used as 1530nm-band pump.

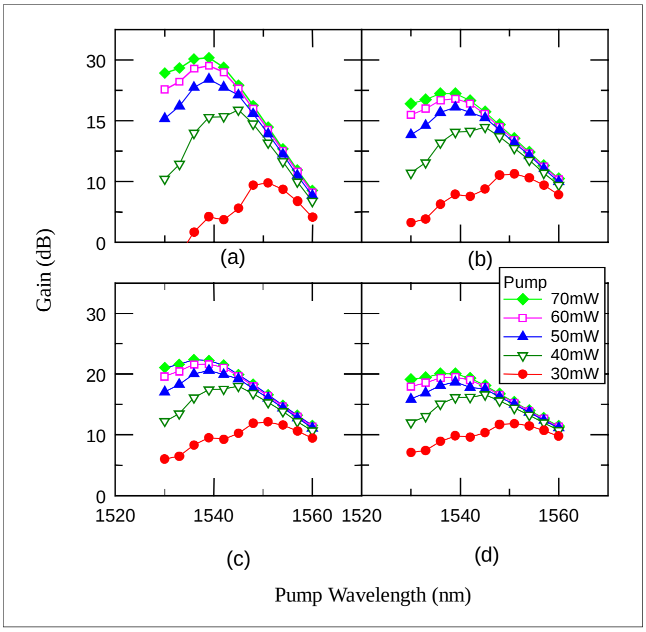

Fig.9. Gain as functions of 1530nm-band pump wavelength and power at the signal wavelengths of (a) 1571.5nm, (b) 1581.5nm, (c) 1591.5nm, and (d) 1601.5nm.

2. Characteristics of 1530nm-Band Pumped L-band EDFA for WDM Signals

The experimental setup for WDM signals is sketched in Fig. 10. Compared with the setup in Fig. 1, the only difference is that we use two coupled TLSs as input signal sources, which consist of a probe and a saturation tone. The power of the saturation tone corresponds to the sum of power of 4 WDM signals and a wavelength of the saturation is 1590nm. Two signal sources are combined by a 3dB coupler. 1533nm was used as pump wavelength in this experiment.

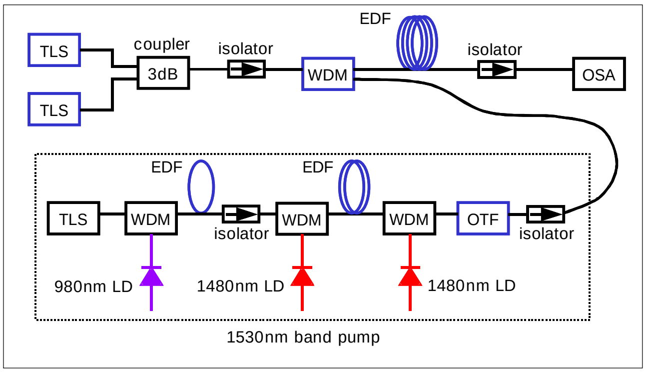

Fig.10. Experimental configuration of 1530nm-band pumped L-band EDFA for WDM signals. TLS: tunable light source; WDM: wavelength-division multiplexer; EDF: erbium-doped fiber; OTF: optical tunable filter.

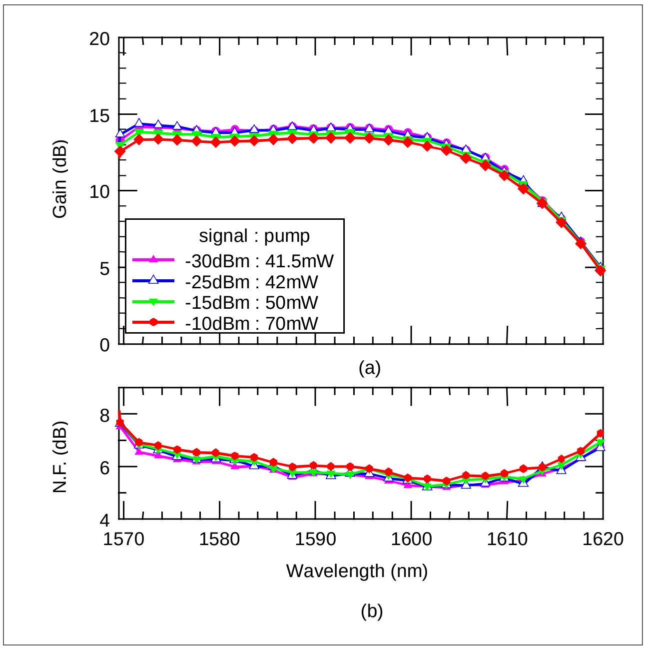

Fig.11. (a) Gain spectra and (b) noise figure spectra of a 1533nm pumped L-band EDFA for WDM signals which were composed of a probe signal and saturation tone. Pump power was varied as 41.5, 42, 50, and 70mW according to power of probe signal of -30, -25, -15, and -10dBm/ch, respectively.

The results of gain and NF are shown in Figs. 11(a) and (b). The power of a probe signal was varied from -30 to -10dBm/ch and the pump power was 41.5, 42, 50 and 70mW, respectively. The characteristics of gain and NF to WDM signals of -30dBm/ch are the same with those to a single signal in Fig. 4. At high power signal input, there is a little decrease of gain and so increase of NF due to gain saturation. Conclusively, in WDM signals experiment, we obtained the same flattened gain profiles with the L-band EDFA of a single channel. Flat gain bandwidth of signal wavelength is 26nm from 1571.5 to 1597.5nm within 0.1dB excursion and 32nm from 1571.5 to 1603.5nm within 1dB excursion at input signal of -10dBm/ch. These results demonstrate that the L-band EDFA using 1530nm-band pump can be used as high gain coefficient amplifier in WDM transmission systems.

Finally, we note that since the EDF length for L-band amplification was limited by maximum available pumping power in our experimental equipments, we used only a 65m EDF in this work. But to generalize the merits of the L-Band EDFA pumped by 1530nm-band, further experiments using longer EDF and high pumping power are required.

IV. CONCLUSIONS

An L-band EDFA with 1530nm-band pumping was investigated. The pump source was composed of a TLS and two C-band EDFAs in cascaded configuration, and was designed to have 23dBm output power. Gain coefficient and NF were measured for pump wavelengths between 1530nm and 1560nm. Gain coefficient and relative PCE of 1545nm pump in 1530nm band was 0.45 dB/mW and 2.25 respectively, which were more than twice compared with those obtained from a conventional 1480nm pump. The L-band EDFA using 1530nm-band pump consumes low optical pump power. NF was 6.36dB with 1530nm pump and 6.55dB with 1533nm pump at the signal wavelength of 1571.5nm, where the NF has the worst value in the measurement range which are increased by less than 1dB compared with 1480nm pumping.

It was proved from the power of ASE spectra that the gain coefficient became smaller with a pump wavelength close to 1560nm because the pump power was not well absorbed. Since the gain spectra as a function of pump wavelength had a 3dB bandwidth of more than 10nm, a broadband pump source can be used as 1530nm-band pump. Within the 1530nm band, it is recommended that wavelength between 1530nm and 1540nm is optimal as pump wavelength for high gain and low NF.

We tested the performances of the L-band EDFA for WDM signals, in which input signal sources was composed of a probe and a saturation tone for 4 WDM signals. The flat gain bandwidth was 26nm for 1571.5 ~ 1597.5nm within 0.1dB excursion and 32nm for 1571.5 ~ 1603.5nm within 1dB excursion at input signal of -10dBm/ch.

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