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# S- plus C-band erbium-doped fiber amplifier in parallel structure

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**Abstract**

A new S- plus C-band erbium-doped fiber amplifier (EDFA) module with coupled structure over 96 nm gain bandwidth of 1480–1576 nm has been experimentally investigated and demonstrated. For this proposed configuration, 30 and 36.2 dB peak gains are observed at 1506 and 1532 nm, respectively, when the input signal power is –25 dBm. In addition, this proposed amplifier module also can provide a broadband amplified spontaneous emission (ASE) light source from 1480 to 1572 nm.


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## 1. Introduction

Wide-band erbium-doped fiber amplifiers (EDFAs) are considerably expected and interested for high-capacity in dense wavelength division multiplexing (DWDM) systems. However, the transmission capacities in DWDM systems were limited by the gain bandwidth of the conventional C-band erbium-doped fibers (EDFs) between 1530 and 1560 nm. Furthermore, the L-band (1560–1610 nm) fiber amplifier techniques have been achieved, such as the EDFAs by using a longer EDF than that of C-band EDFAs [1], the fiber Raman amplifiers [2], and the different hybrid amplifiers [3]. In addition, a wideband EDFA from C- to L-band by employing coupled structure has also studied [4]. Recently, an new S-band (1450–1530 nm) amplification technique, which utilizes erbium-doped silica fiber with depressed cladding design and 980 nm pump laser to generate EDF gain extension effects, has been reported [5].

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Therefore, by employing a coupled structure and the new S-band amplifier module can retrieve the wide gain bandwidth from S- plus C-band. In this paper, we have proposed and experimentally demonstrated a coupled structure and S- plus C-band EDFA module with 96 nm gain bandwidth of 1480–1576 nm. In addition, the performance of this proposed EDFA module has also been studied.

## 2. Experiments and discussions

Fig. 1 shows the experimental setup for the wideband EDFA module from S- to C-bands by using a coupled structure. This configuration is constructed by two 1480/1550 nm WDM couplers ($W_1$), an S-band EDFA module composed of two EDFA stages and a power-sharing 980 nm pump laser, and a conventional C-band EDFA module. Two WDM couples were used to connect two EDFA modules in parallel, and the output ranges of the port "1", "2" and "3" were 1480–1600, 1480–1520 and 1520–1600 nm, respectively, as seen in Fig. 1. The S-band EDF inside EDFA module has a depressed cladding design in order to provide a sharp, high attenuation, long wavelength cutoff filter into active fibers. Then, the composition of the core is approximately 2.5% $GeO_2$, 5.5% $Al_2O_3$ and 92% $SiO_2$, with 0.15 wt% Erbium. The depressed cladding is approximately 3% Fluorine, 0.5% $P_2O_5$ and 96.5% $SiO_2$. The numerical aperture of the core, relative to the depressed cladding, is 0.22. The S-band EDF inside EDFA module has a depressed cladding design in order to provide a sharp, high attenuation, long wavelength cutoff filter in the EDF. The cutoff wavelength is near at 1530 nm. The fabrication uses standard MCVD processes and solution doping for incorporation of aluminum and erbium. The core and cladding diameters are 4 and 22 μm, respectively. The numerical aperture of the core, relative to the depressed cladding, is 0.22. The background loss is less than 5 dB km$^{-1}$. This S-band EDFA was fusion direct spliced to SMF-28 using standard setting. Typical splice losses were 0.5 dB. The EDFs in the first and second stages have different characteristics. The fiber in the first stage has the fiber length of 20 m, and can provide low noise figure and medium gain by forward pumping. The fiber in the second stage has the fiber length of 30 m, and can produce large output power by backward pumping. In addition, the optical isolator between these two stages can reduce

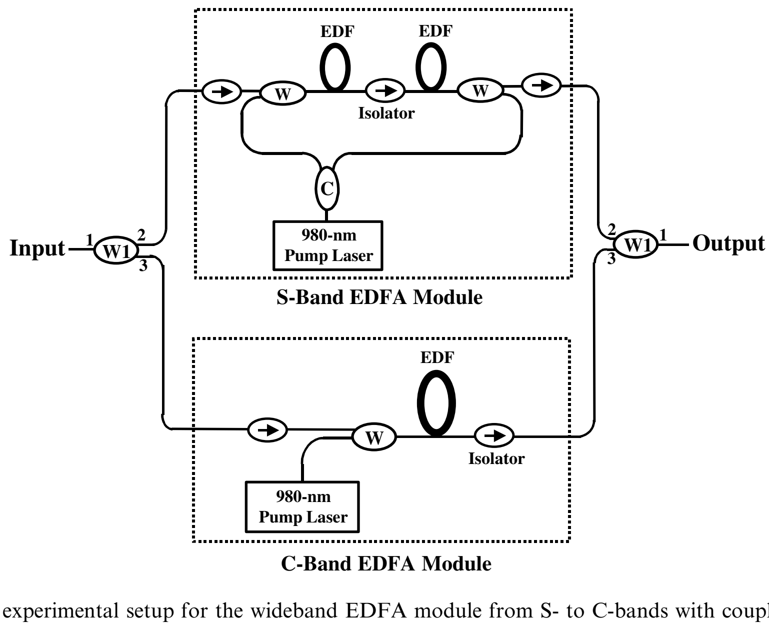


Fig. 1. The experimental setup for the wideband EDFA module from S- to C-bands with coupled structure.

backward amplified spontaneous emission (ASE) and improve noise figure performance. The total pump power of this amplifier module can be up to 280 mW while the bias current is operated at 356 mA. Furthermore, the evolution from a standard EDFA to this S-band design by the introduction of a continuous long wavelength cutoff filter in the EDF. Although the spectrum indicates strong gain at S-band wavelengths, the gain cannot be realized because of strong ASE at the 1530 nm peak, which limits the length of the population inversion. Introduction of a progressively sharper long wavelength cutoff filter suppresses the gain in the C- and L-bands, so that the S-band region can exhibit increasing gain, as ASE from the 1530 nm peak does not grow and limit the population inversion. Final result is a complete suppression of the longer wavelength gain, resulting in a usable high net gain in the S-band. However, the C-band EDFA module composed of a 980 nm pump power of 140 mW, a 980/1550 nm WDM coupler, a EDF (HighWave-742) length of 10 m long and two optical isolators.

To ensure the performances for this proposed amplifier module in Fig. 1, the input signal power Pin = −5, −15 and −25 dBm are used to probe the gain and noise figure spectra, respectively. Fig. 2 shows the gain and noise figure spectra for the S-band EDFA module of Fig. 1. The inset of Fig. 2 also shows the ASE spectrum with 40 nm bandwidth of 1480–1520 nm for the S-band amplifier module. The gain and noise figure of the S-band EDFA can reach 34.1 and 6.8 dB at 1506 nm when the input signal power is −25 dBm as shown in Fig. 2. It also shows the gain of >10 dB and the noise figure of 6.7–13.5 dB over the wavelength of 1480–1520 nm with −5 dBm input signal power. Fig. 3 shows the gain and noise figure spectra from 1520 to 1580 nm for the C-band EDFA module of Fig. 1. As the same above operation conditions, 38.6 dB peak gain and 5.4 dB noise figure can be obtained, and the gain of >12 dB and the noise figure of <5.8 dB over the wavelengths of 1520–1580 nm are observed in Fig. 3. Figs. 4(a) and (b) indicate the gain and noise figure spectra of the proposed wideband EDFA module in Fig. 1 while the input signal power Pin = −5, −15 and −25 dBm, respectively. The inset of Fig. 4(a) shows the ASE spectrum over 98 nm bandwidth of 1480–1572 nm for this proposed structure as the optical output power level above −40 dBm. Besides, the inset of Fig. 4(b) presents that the insertion loss spectra of port "2" and "3" for two 1480/1550 nm WDM couplers, and two loss curves fold downward at around 1522 nm. Fig. 4(a) represents the gain of >10 dB over 96 nm gain bandwidth of 1480–1576 nm while the input signal power of <−5 dBm. Due to the insertion loss of two WDM couplers, the different gain spectra of this proposed amplifier is smaller

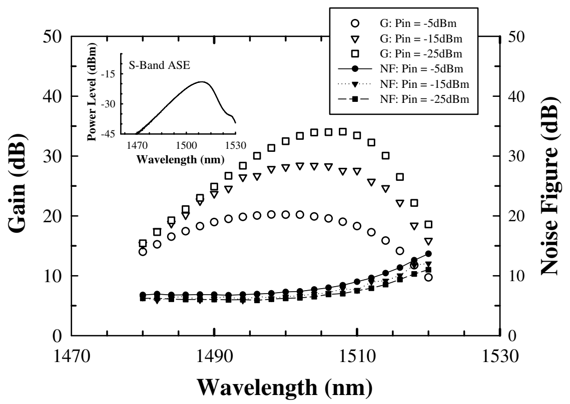


Fig. 2. The gain and noise figure spectra for the S-band EDFA module while the input signal powers Pin = −5, −15, and −25 dBm, respectively. The inset of this figure is ASE spectrum of the S-band amplifier module.

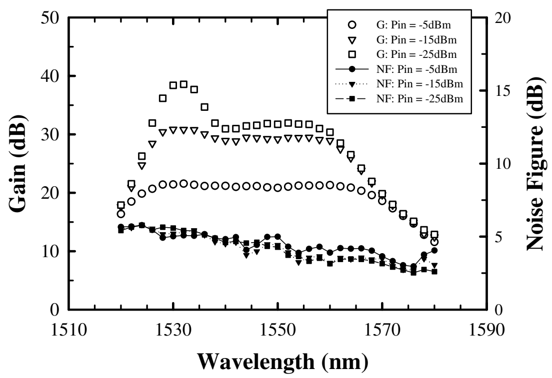


Fig. 3. The gain and noise figure spectra of the C-band EDFA module while the input signal power Pin = −5, −15 and −25 dBm, respectively.

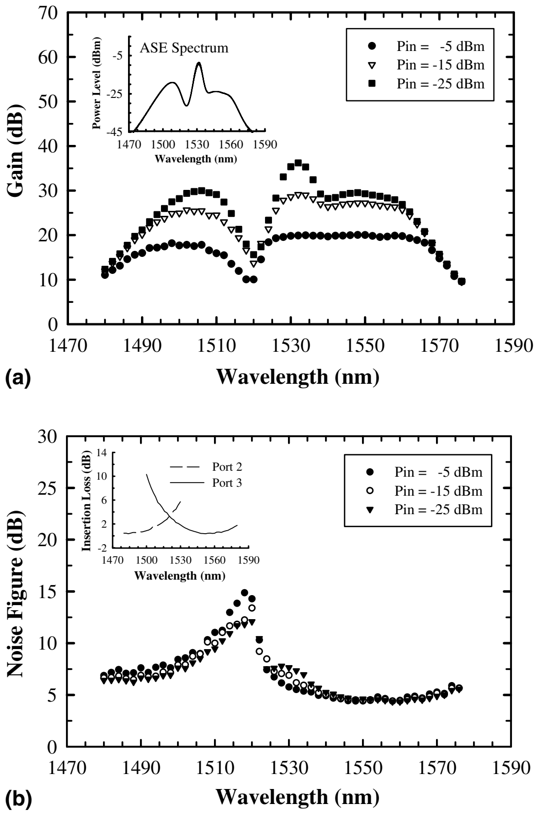


Fig. 4. (a) The gain and (b) noise figure spectra of the proposed configuration in Fig. 1 while the input signal powers Pin = −5, −15 and −25 dBm, respectively. The inset of (a) and (b) are the ASE spectrum of the proposed structure and the insertion loss of 1480/1550 nm WDM coupler versus operating wavelength, respectively.

than that of the S- and C-band amplifier individually, and the gain spectra drops at near 1522 nm, as seen in Fig. 4(a). Compared with mentioned S- and C-band EDFA individually, the noise figure also degraded above 0.7–1.3 dB (especially between 1516 and 1524 nm) from 1480 to 1576 nm as shown in Fig. 4(b). In addition, 30 dB peak gain with 8.2 dB noise figure, and 36.2 dB peak gain with 7.3 dB noise figure can be observed at 1506 and 1532 nm, respectively, while the input signal power of −25 dBm. However, the insertion loss ofthe band-pass coupler seem a little high in the 1520 nm range and the consequent amplifier noise figure in that region is well over 10 dB for all input conditions for the wavelengths from 1510 to 1526 nm as shown in Fig. 4(b). According to Fig. 4, the gain and noise figure spectra also show the behavior and performance of that when three different input signal power levels (Pin = −5, −15 and −25 dBm) are applied in the experiment, respectively. Therefore, the proposed EDFA can be used to act as the in-line, pre- or post-amplifier in the optical WDM systems. Compared with the past broadband amplifier techniques [6,7], which used thulium-doped fiber type or Raman amplification, the proposed amplifier employs two EDF amplifier modules in parallel configuration over the gain bandwidth from 1480 to 1576 nm. The proposed EDFA has the advantage of wide bandwidth, potentially lower cost and simple architecture.

As a result, this proposed amplifier module based on coupled structure could achieve 96 nm gain bandwidth of 1480–1576 nm and the gain of >10 dB has been reached simultaneously when the input signal power level of <−5 dBm. Besides, this proposed amplifier module also provides a broadband ASE light source from1480 to 1572 nm. Therefore, this proposed EDFA module may be used in WDM networks.

## 3. Conclusion

In summary, we have experimentally investigated and demonstrated a new S- plus C-bands EDFA module in parallel structure over 96 nm gain bandwidth of 1480–1576 nm when the gain of >10 dB (the input signal power level could great than −5 dBm) over the bandwidth of 1480–1576 nm. For the proposed EDFA, 30 dB peak gain with 8.2 dB noise figure and 36.2 dB peak gain with 7.2 dB noise figure can be observed at 1506 and 1532 nm, respectively, while the input signal power of −25 dBm. In addition, this proposed amplifier module also can provide a broadband ASE light source from 1480 to 1578 nm while the optical output level above −40 dBm.

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