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Measurement of multi-wavelength optical amplifier by using the I/O power-curve fitting technique

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ABSTRACT

A low-cost and accurate measurement scheme for characterizing multi-wavelength optical amplifiers is experimentally demonstrated by using an amplified spontaneous emission source and a DWDM multiplexer. By linearly fitting the input and output optical spectral densities, the gain and noise figure of the optical amplifier are determined. The measured results agree well with the data obtained by time-domain-extinction method.

1. Introduction

Broadband optical amplifiers can simultaneously amplify dozens of wavelengths to compensate the signal power losses and have become the key components in a dense wavelength-division multiplexing (DWDM) system. However, the measurements to characterize the gain and noise figure (NF) of the multi-wavelength optical amplifiers are always expensive. Although the time-domain-extinction (TDE) method [1] and the spectral interpolation method [2] are usually applied to measure the gain and NF of the broadband optical amplifiers, these techniques require a large number of distributed feedback (DFB) lasers. To lower the implementation cost, the techniques by using a reduced set of saturating sources or a broadband amplified spontaneous emission (ASE) source have been proposed [3,4]. In the reduced source approximation [3], the measurement accuracy is limited by the presence of spectral hole-burning, which distorts the gain spectral shape [5]. The broadband ASE source technique is typically combined with the TDE method [4], which requires the expensive instruments such as acousto-optic modulators with high extinction ratios. Therefore, Gupta and Qian proposed a low-cost scheme by linearly fitting the input and output spectral densities of a broadband optical amplifier [6]. The linear relationship between the input and output optical spectra is least-square fitted and then the gain and NF can be derived from the slope and intercept [6,7]. We call this method as the Input/Output (I/O) power-curve fitting technique. However, the measurement accuracy for the practical multi-channel amplification of the broadband optical amplifier has not been demonstrated in their experiments. In this paper, we performed the measurement of the multi-wavelength optical amplifiers by using an ASE source, a DWDM multiplexer, and applying the I/O power-curve fitting method. The accuracy of gain and NF measurement for a tested erbium-doped fiber amplifier (EDFA) is demonstrated. The results show to be comparable to the data measured by the conventional TDE method (Anritsu ME7890C).

2. Measurement

The measurement setup of the proposed method is illustrated in Fig. 1. The broadband light from the ASE source are split to N outputs by a power splitter, and then the N split lights are all coupled to a DWDM multiplexer. The filtered and multiplexed light is used as the multi-wavelength input signal for the tested amplifier. Comparing with the multi-wavelength laser light, we believe that the similar spectral shape of the proposed multi-band input signal can reduce the effect of the spectral hole-burning in the inhomogeneous gain medium. In this work, the tested EDFAs are respectively

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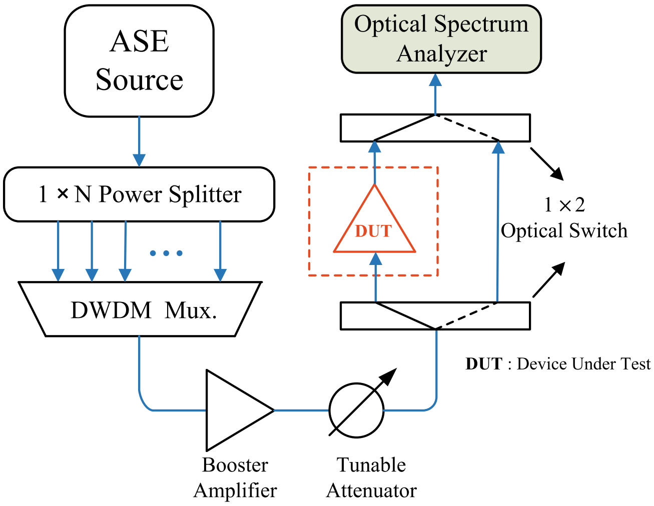

Fig. 1. Schematic setup of the measurement.

a C-band forward-pumped amplifier and a bidirectional-pumped amplifier. A booster amplifier is applied to amplify the input signal power for measuring the characteristics of the test EDFA in gain saturation region. An optical spectrum analyzer (OSA) and two 1 × 2 switches are applied to obtain the input and output spectra of the tested EDFA without changing any connectors.

According to the conventional definitions of gain and NF [8], the two parameters can be expressed as

$$G(\lambda) \equiv \frac{P_{out}(\lambda) - P_{ASE}(\lambda)}{P_{in}(\lambda)} \tag{1}$$

$$NF(\lambda) \equiv \frac{SNR_{in}}{SNR_{out}} = \frac{1}{G(\lambda)}\left[1 + \frac{\lambda^3 P_{ASE}(\lambda)}{hc^2 \Delta\lambda}\right] \tag{2}$$

where $P_{in}(\lambda)$, $P_{out}(\lambda)$, and $P_{ASE}(\lambda)$ are the optical powers of the input, output, and ASE lights within bandwidth $\Delta\lambda$ (centered at wavelength λ), respectively, h is Planck's constant, and c is the velocity of the light in vacuum. The bandwidth $\Delta\lambda$ is the wavelength resolution of the OSA. In Eq. (1), the gain $G(\lambda)$ and $P_{ASE}(\lambda)$ are respectively the slope and intercept of the linear relationship between $P_{in}(\lambda)$ and $P_{out}(\lambda)$. The input and output spectra of the tested EDFA are shown in Fig. 2. The corresponding relationship between $P_{in}(\lambda)$ and $P_{out}(\lambda)$ is obtained from the data points in each spectral-slope region, where the spectral power rapidly varies with the wavelength.

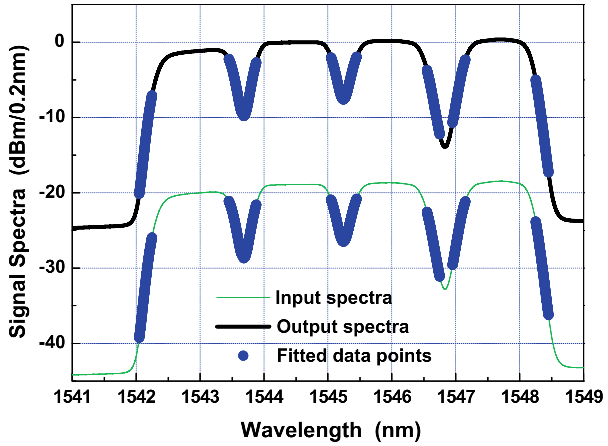

Fig. 2. Input and output spectra of the tested EDFA for the total input power of –5 dBm.

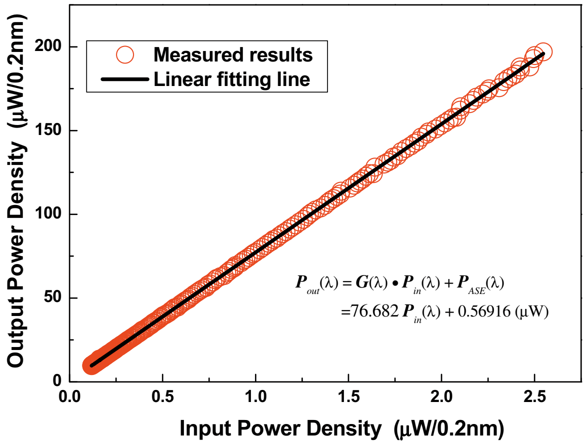

Fig. 3. Plot of output power density $P_{out}(\lambda)$ versus input power density $P_{in}(\lambda)$.

Applying the linear relationship between $P_{in}(\lambda)$ and $P_{out}(\lambda)$ as expressed in Eq. (1), $G(\lambda)$ and $P_{ASE}(\lambda)$ can be determined by using a least-square linear fitting of $P_{in}(\lambda)$ versus $P_{out}(\lambda)$, as shown in Fig. 3. We assume $G(\lambda)$ and $P_{ASE}(\lambda)$ are constants in the narrow sampling spectral-slope region. To compensate the error of this assumption, the gain and ASE power at each central wavelength are calculated by averaging the gains and ASE powers at the two side slopes of each channel. Finally, the NF can be derived by using the Eq. (2).

3. Results and discussion

In order to verify the accuracy of the proposed measurement, the gain and NF of a forward-pumped EDFA were measured with three-wavelength input lights. A thin-film-filter type multiplexer (TFF mux.) with channel spacing of 200 GHz and an arrayed waveguide grating multiplexer (AWG mux.) with 100 GHz channel spacing were applied to multiplex the input lights. Table 1 shows the measured results by using the I/O power-curve fitting method and the standard three-wavelength TDE method, where the data in Table 1 are the performance of the tested EDFA for total input power of 30 dBm [7]. Based on the experimental results, it can be seen that both the gain and NF obtained by the proposed method are in good agreement with the measured results of the conventional TDE method. The accuracy of the I/O power-curve fitting method is independent of the channel spacing and the different kind DWDM filters.

We further studied the accuracy of the proposed method for the EDFA under various total input powers. The gain and NF of a bidirectional-pumped EDFA with four-wavelength input lights were

Table 1
The measured gain and NF of the tested EDFA by using various multiplexers.

Multiplexer	Method	Wavelength (nm)	G (dB)	NF (dB)
TFF	I/O power-curve fitting	1546.08	29.49	5.47
		1547.72	29.37	5.44
		1549.31	29.22	5.38
	TDE	1546.92	29.40	5.64
		1547.72	29.28	5.58
		1548.52	29.21	5.41
AWG	I/O power-curve fitting	1546.08	29.46	5.46
		1547.72	29.37	5.47
		1549.31	29.30	5.41
	TDE	1546.92	29.55	5.43
		1547.72	29.36	5.52
		1548.52	29.47	5.28

Table 2
The measured gain and NF of the tested EDFA for the total input powers of −30 dBm and −5 dBm.

Total input power	Method	Wavelength (nm)	G (dB)	NF (dB)
−30 dBm	I/O power-curve fitting	1542.89	33.07	4.59
		1544.58	32.90	4.48
		1546.14	32.57	4.41
		1547.61	32.17	4.33
	TDE	1542.89	33.74	4.43
		1544.58	33.49	4.44
		1546.14	33.14	4.32
		1547.61	32.72	4.27
−5 dBm	I/O power-curve fitting	1542.89	18.85	4.82
		1544.58	18.86	4.69
		1546.14	18.85	4.81
		1547.61	18.83	4.68
	TDE	1542.89	19.45	4.42
		1544.58	19.43	4.48
		1546.14	19.35	4.47
		1547.61	19.34	4.41

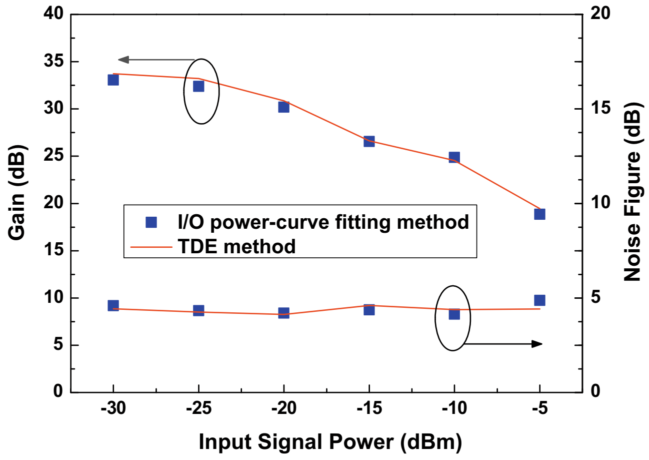

Fig. 4. Comparison of the gain and noise figure measured by the I/O power-curve fitting method and the time-domain-extinction method at 1542.89 nm wavelength under various four-wavelength input powers.

measured. The above-mentioned TFF multiplexer was applied to multiplex four-wavelength input lights. The measured results for the total input power of −30 dBm and −5 dBm are shown in Table 2. In Fig. 4, the solid squares and the solid lines are the data measured by the I/O power-curve fitting method and the TDE method, respectively. The results show that the I/O power-curve fitting method excellently match the data obtained by the TDE method. Therefore, it is verified that the I/O power-curve fitting method is still accurate for the total input power of −5 dBm.

However, using the I/O power-curve fitting method, we also find that there is a significant error in determining the ASE power for the total input power of 0 dBm. In order to study the reason of the error, we have estimated the maximum input signal power suitable for the use of the I/O power-curve fitting technique by a statistic method. A relative error *er* is defined as

$$er = \frac{\sqrt{\frac{1}{N}\sum^{N}(P_{out}(\lambda) - P^{f}_{out}(\lambda))^2}}{P_{ASE}(\lambda)} \tag{3}$$

where $P^{f}_{out}(\lambda)$ is the output power devised from the linear fitting of $P_{in}(\lambda)$ versus $P_{out}(\lambda)$, N is the number of experimental data pairs (P_{in}, P_{out}) and $P_{ASE}(\lambda)$ denotes the ASE power measured by TDE method. The relative error was the ratio of the standard deviation in the linear fitting to the practical power of the ASE light. In this work, the relative error *er* was calculated by using the data at the short-wavelength slope of the passband 1542.89 nm. The obtained errors in the conditions of the total input power −30, −20, −10, and 0 dBm are 0.08%, 0.29%, 2.11%, and 48.53%, respectively. From the calculated results, we can see that the error of our proposed measurement will be large if the ASE power is decreased to the same order as the standard deviation of the linear fitting while increasing the input signal power.

We have investigated the conditions under which good accuracy can be achieved. The sampling data points used in linear fitting should cover the steepest range of each filter edge in a narrow wavelength range, and a sufficient number of data points are required for a good linear fitting. We took 10001 sampling points in the span range of 10 nm, and 200 data pairs (P_{in}, P_{out}) were used in each linear fitting. The calculation accuracy of the NF can also be affected by the error in wavelength resolution of the OSA. Moreover, for the stable spectral characteristics of the DWDM filters, the DWDM multiplexer must have temperature-independent performance, or the temperature for it should be fixed during measuring the input and output spectra.

4. Conclusion

In this paper, we have demonstrated a simple and accurate gain and NF measurement of the multi-wavelength optical amplifiers by using a broadband source, a DWDM multiplexer and the I/O power-curve fitting method. In the measurement, the filtered and multiplexed lights replace the lights multiplexed from a large number of expensive DFB laser modules and reduce the effects of spectral hole-burning in EDF. The gain and NF are obtained from the linear fitting of the input/output optical spectra and the experimental results are in good agreement with the data obtained by the conventional time-domain-extinction method. We believe that the proposed technique is a very powerful method for measuring the gain and NF during the manufacturing process of multi-wavelength optical amplifiers due to its accuracy and simplicity in the experimental setup and operation.

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