Gain flattened erbium-doped amplifier with 34 nm flat bandwidth

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A gain-flattened two-stage erbium-based fibre amplifier module, structured by an erbium-doped waveguide amplifier and an erbium-doped fibre amplifier in serial, is proposed and demonstrated experimentally. In an operating range of 1528 to 1562 nm, all the gain is above 35 dB and the noise figure is distributed from 5.5 to 6.7 dB, and ±1.1 dB maximum gain variation is retrieved at an input saturation power of −25 dBm. As a result, the proposed amplifier not only enhances gain value but possesses flatness in the operating region.

Introduction: Because of the characteristics of erbium-doped fibres (EDFs), the gain spectra of erbium-doped fibre amplifiers (EDFAs) present non-flat and input-dependent behaviours. Therefore, a gain-flattened function is very important for the EDFAs dynamically working on wavelength division multiplexed (WDM) communication networks. Mainly, the gain profiles of EDFAs can be flattened by several techniques, such as by doping the material composition in the erbium-doped fibre (EDF) [1], or using optical filters to compensate for variations in the gain spectrum [2–8]. Various kinds of optical filters have been demonstrated for this application, including long-period fibre gratings [2, 3], fibre Bragg gratings (FBGs) [4], fibre acousto-optic tunable filters [5, 6], Mach-Zehnder (M-Z) filters [7], and a split-beam Fourier filter [8]. Recently, an adjustable filter in the form of a high-birefringence fibre loop mirror (HiBi-FLM) and Raman amplifiers with multi-pump to flatten the gain profiles were also reported [9, 10].

In this Letter, we propose and investigate a gain-flattened two-stage erbium-based fibre amplifier (EBFA) module, constructed by an erbium-doped waveguide amplifier (EDWA) and an EDFA in serial. Therefore, the observed gain of the proposed amplifier not only enhances the gain but also possesses flatness.

Experiment and results: The proposed gain-flattened two-stage erbium-based fibre amplifier module in serial is illustrated in Fig. 1. The first stage is an EDWA and the second is an EDFA. Two tunable laser sources are used to act as a saturation tone and probe tone, respectively. An optical spectrum analyser (OSA) with 0.05 nm resolution is used to measure gain and the noise figure. Owing to the homogeneously broadened gain characteristics, the multiwavelength input signal in a WDM system can be simulated using a saturation tone with a power equal to the aggregated power of the multiwavelength input signal [11]. Because substantial spectral-hole burning was observed near 1550 nm [3], a saturation tone is set at 1535 nm with −25 dBm in this experiment to simulate a multiwavelength input signal. A probe light was 20 dB below the saturating tone so as not to alter the ion inversion and change the erbium amplifier spectrum.

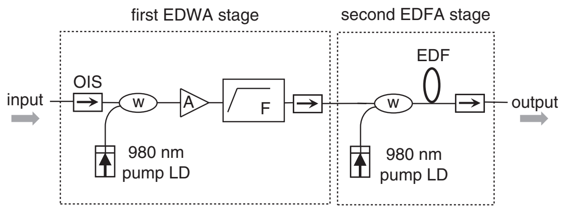

Fig. 1 *Proposed structure for two-stage gain-flattened EBFA module, structured by EDWA and EDFA in serial*

A: waveguide gain media; W: 980/1550 nm WDM coupler; F: pump kill filter; OIS: optical isolator; EDF: erbium-doped fibre; EDWA: erbium-doped waveguide amplifier; EDFA: erbium-doped fibre amplifier

The EDWA, which is manufactured via two-step ion-exchange process, has the advantage of inheriting the known properties of the EDFA. All optical performances are measured when the laser pump diode current equals 440 mA at ambient temperature. Fig. 2 shows gain and noise figure profiles of the EDWA for −25 dBm input saturation power in an operating range of 1528 to 1562 nm. However, the peak gain and noise figure of 30.1 and 5.7 dB, respectively, are also observed at 1532 nm, and the noise figure distributes from 5 to 6.3 dB in the wavelengths of 1524 to 1572 nm, when the input saturation power is −25 dBm. The maximum gain variation of 4.8 dB is also retrieved in Fig. 2 over the wavelengths of 1524 to 1562 nm.

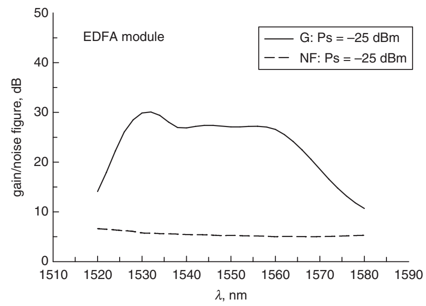

Fig. 2 *Gain and noise figure spectra of EDWA in bandwidth 1520 to 1580 nm for −25 dBm input saturation power*

The second EDFA stage consists of a 10 m-long EDF, a 980 nm pump laser, a 980/1550 nm WDM coupler and an optical isolator (OIS). Pump power of the 980 nm laser operates at 72 mW. Fig. 3 shows the gain and noise figure spectra of the EDFA for −25 dBm input saturation power over the operating range 1528 to 1562 nm. Simultaneously, 36.2 dB peak gain and 4.8 dB noise figure are observed at 1532 nm for −25 dBm input saturation power. Maximum gain variation of 12.2 dB is also retrieved in the operating region of 1524 to 1562 nm, as shown in Fig. 3.

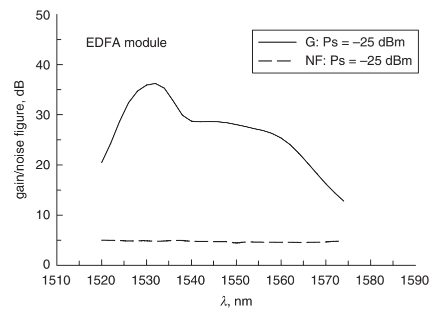

Fig. 3 *Gain and noise figure spectra of EDFA with 10 m-long EDF length in bandwidth 1520 to 1580 nm for −25 dBm input saturation power with pump power of 72 mW*

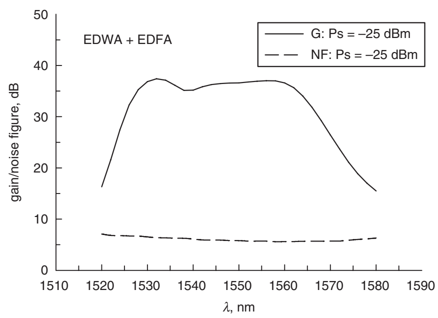

Fig. 4 *Gain and noise figure spectra of proposed gain-flattened two-stage EBFA module in bandwidth 1520 to 1580 nm for −25 dBm input saturation power*

A possible mechanism is that the EDWA and the EDFA have complementary spectroscopy and the gain saturation effect to achieve the gain flattening. Therefore, Fig. 4 shows the gain and noise figure spectra of the proposed gain-flattened amplifier for −25 dBm input saturation power in the operating range 1528 to 1562 nm. Fig. 4 presents two peak gains of 37.4 and 37.0 dB at 1532 and 1556 nm, respectively, and maximal gain variation of ± 1.1 dB is also retrieved, for −25 dBm input saturation power in the same operating range, as shown in Fig. 4. From the above results for this gain-flattened EBFA, it can be seen that the proposed EBFA can approach gain-flattening and also enhance gain value owing to the gain saturation effect and the two-stage amplifier. In accordance with the experimental results, the EBFA module increases all the gain (all above 35 dB) in the wavelengths 1528 to 1562 nm, and the gain profile also maintains flatness with the maximum variation of ± 1.1 dB for −25 dBm input saturation power. In general, the gain-flattened EDFAs used the various optical filters to filter the redundant ASE to maintain the flattening behaviuor. However, past methods can cause loss and gain degradation of EDFAs. As a result, our proposed EBFA not only flattens the shape of the gain spectrum but enhances gain value.

To demonstrate the performance of the proposed gain-flattened EBFA module, a bit error rate (BER) was measured in this experiment. A test input signal at 1550 nm was modulated by a 2.5 Gbit/s non-return-to-zero (NRZ) pseudorandom binary sequence (PRBS) with a pattern length of $2^{31} - 1$ on a $LiNbO_3$ electro-optical (EO) modulator. However, the BER performance should be back-to-back without the proposed EDF-based amplifier module, characterising the transmitter and receiver. A 2.5 Gbit/s optical receiver was used to measure the gain-flattened EBFA system performance. Therefore, Fig. 5 shows the measured BER of the proposed optical amplifier against the received power for the back-to-back type and the test signal through the gain-flattened EBFA module. Therefore, while a test input signal passes through the amplifier module, the observed optical power penalty is nearly 0.4 dB, while the BER is 10^{-9}.

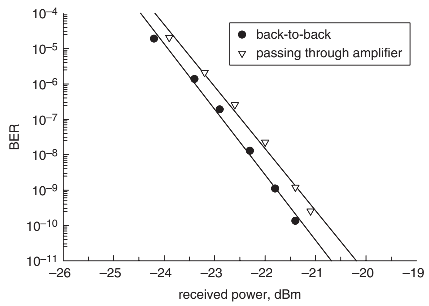

Fig. 5 *Performance of BER at test signal of 1550 nm in 2.5 Gbit/s modulated system for back-to-back type and proposed gain-flattened EBFA module*

Conclusion: We propose and have demonstrated experimentally a gain-flattened two-stage fibre amplifier module, structured by an EDWA and an EDFA in serial structure. In the operating range of 1528 to 1562 nm, obtained gain is larger than 35 dB and the noise figure is distributed from 5.5 to 6.7 dB, and a maximum gain variation of ± 1.1 dB is retrieved simultaneously when the input saturation power is −25 dBm. Therefore, the proposed amplifier not only keeps the gain flattening but enhances gain value in the bandwidth 1528 to 1562 nm.

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References

1 Yamada, M., *et al.*: 'Fluoride-based erbium-doped fibre amplifier with inherently flat gain spectrum', *IEEE Photonics Technol. Lett.*, 1996, **8**, pp. 882–884

2 Pandit, M.K., *et al.*: 'Tunable long period fibre gratings for EDFA gain and ASE equalization', *Microw. Opt. Technol. Lett.*, 1999, **25**, pp. 181–184

3 Wysocki, P.F., *et al.*: 'Broad-band erbium-doped fibre amplifier flattened beyond 40 nm using long-period grating filter', *IEEE Photonics Technol. Lett.*, 1997, **9**, pp. 1343–1345

4 Liaw, S.K., Ho, K.P., and Chi, S.: 'Dynamic power-equalized EDFA module based on strain tunable fibre Bragg gratings', *IEEE Photonics Technol. Lett.*, 1999, **11**, pp. 797–799

5 Feced, R., *et al.*: 'Acoustooptic attenuation filters based on tapered optical fibres', *IEEE J. Sel. Top. Quantum Electron.*, 1999, **5**, (3), pp. 1278–1288

6 Yun, S.K., *et al.*: 'Dynamic erbium-doped fibre amplifier based on active gain flattening with fibre acoustooptic tunable filter', *IEEE Photonics Technol. Lett.*, 1999, **11**, pp. 1229–1231

7 Nilsson, J., *et al.*: 'Simple gain-flattened erbium-doped fibre amplifier with a wide dynamic range'. OSA Tech. Dig. Optical Fiber Communications Conf., Washington, DC, USA, Optical Society of America, 1997, p. 163

8 Betts, R.A., Frisken, S.J., and Wong, D.: 'Split-beam Fourier filter and its application in a gain-flattened EDFA'. OSA Tech. Dig. Optical Fiber Communications Conf., Washington, DC, USA, Optical Society of America, 1995, pp. 80–81

9 Li, S., Chiang, K.S., and Gambling, W.A.: 'Gain flattening of erbium-doped fibre amplifier using high birefringence fibre loop mirror', *IEEE Photonics Technol. Lett.*, 2001, **13**, pp. 942–944

10 Ania-Castanon, J.D., *et al.*: 'Simple design method for gain-flattened three-pump Raman amplifiers'. LEOS'02, 2002, Vol. 2, pp. 500–501

11 Baney, D.M., and Stimple, J.: 'WDM EDFA gain characterization with a reduced set of saturating channels', *IEEE Photonics Technol. Lett.*, 1996, **8**, pp. 1615–1617