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Broad-band EDFA gain flattening by using an embedded long-period fiber grating filter

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Abstract

An erbium-doped fiber amplifier (EDFA) gain flattening technique using an embedded long period grating (ELPG) is proposed. By bending the ELPG, due to different coupling strengths yielded from different bending curvatures, it can be used for both the static and dynamic gain flattening despite of the different pump currents of the EDFA. The experimental results demonstrate that the flattened gain region of 34 nm can be achieved within 1 dB ripple.

Keywords: Embedded long period grating (ELPG); EDFA gain flattening; Bending jig setup

1. Introduction

Erbium-doped fiber amplifier (EDFA) is widely applied in optical fiber sensors and optical communication systems because of its broad-band gain region from 1525 to 1565 nm. However, its output power spectral density varies considerably with a marked peak near 1530 nm, which is not suitable for some amplitude modulation (AM) sensing applications and wavelength-division multiplexed (WDM) communication systems when the number of channels increases. The use of a long period grating (LPG) to compensate the EDFA gain spectrum has been taken much attraction because of its simple configuration, low insertion loss and back-reflection compared with other devices such as the micro-opto-mechanical interferometric mirror with variable reflectivity, the acousto-

optic tunable filter or the cascade of variable couplers and delay lines [1–3].

For different pump current levels, the spectral density of the EDFA varies. It has the highest peak around 1530 nm, hence, in order to obtain a flat gain across the EDFA gain spectrum, a device with dynamic attenuation control ability is required for this compensation. By using the LPG as a variable gain equalizer, a few techniques have been demonstrated, such as using Mach-Zehnder configuration [4], thermal method [5] and LPG bending method [6]. Among all of them, the LPG bending method worked on the principle that the amplitude of the resonance dip of the LPG spectrum changed with bending whereas its resonance wavelength remained relatively constant. This was achieved by fabricating the LPG using a CO_2 laser on a section of bending-insensitive fiber. However, its bending sensitivity was orientation dependent which was due to the fabrication using the CO_2 laser and thus it was not applicable in some systems. In this paper, another promising technique for gain flattening is demonstrated by using an LPG, which is fabricated on a normal standard single mode fiber and embedded in carbon–fiber composite material. Using this embedded LPG (ELPG) for EDFA gain equalization does not require expensive and complicated setup such as using variable coupler as Mach-Zehnder configuration. This promotes ease of maintenance and reduction of overall system cost. The use of thermally controlled method to induce LPG and to tune the latter's resonance dip although is effective, this change in thermal temperature will also cause the resonance wavelength to shift. This might causes the LPGs resonance wavelength to shift out of the intended location, 1530 nm, of the optical peak in the EDFAs gain spectrum. Therefore, the effectiveness of gain equalizing the EDFAs gain spectrum is reduced. Bending of the ELPG however promotes changes in the resonance dip while preserving the resonance wavelength, as it will be demonstrated in the later section. This yields higher effectiveness of achieving gain equalization. Unlike the CO_2 fabricated LPG, the LPG used in this work is fabricated using UV illumination on standard telecommunications single mode fiber. Hence, there is no orientation dependency as the birefringence across the whole fiber is negligible. Lastly, as LPG is embedded within the carbon–fiber composite material, the high-strength carbon–fiber material provides addition protection to the LPG, which improves the overall ruggedness of the system. The fabrication of the ELPG is described in Section 2, and the experimental results and discussion are presented in Section 3. Finally, a conclusion is given in Section 4.

2. Fabrication of ELPG

The LPG was fabricated using the amplitude mask technique on a section of H_2-loaded standard telecommunication single mode fiber. The LPG was manufactured by using a KrF excimer laser with an amplitude mask of appropriate periodicity of 450 μm. In fabricating the LPG, it was important that both of the depth and the wavelength location of the resonance dip of the cladding mode to be located at the 1530 nm region to match those of the peak at the 1530 nm region of the EDFAs gain spectrum. The fabrication process carried out was through normal amplitude mask UV irradiation technique. The growth of the LPG spectrum was monitored throughout the whole

fabrication process by an optical spectrum analyzer (OSA, Ando AQ6317) and a tunable laser source (TLS, Ando AQ4321D). The LPG was annealed at 85 °C for around 6 h, in which the purpose was for the stabilization of the LPG and the LPG transmission spectrum after annealing is shown in Fig. 1.

In the embedding process, individual pieces of carbon– fiber composite prepegs (Hexcel Hexply® 913) were stacked on top of each other forming a carbon–fiber composite laminate. There were two purposes to why the LPG was embedded into the carbon–fiber composite laminate. Carbon–fiber composite laminate was chosen as it offered good mechanical performance such as high tensile strength, lightweight and resistance to environmental corrosion. The other important feature of the carbon–fiber composite with high strength was that it remained elastic until total deformation [7]. In a carbon–fiber composite laminate, a layer of epoxy or matrix was holding carbon–fiber together forming pieces of laminate. By embedding the optical fiber with the inscribed LPG into the carbon–fiber composite laminates, a layer of matrix would be surrounding the optical fiber. Results have shown that as higher refractive index of the matrix as compared to the refractive index of the optical fiber cladding [8]. With the external medium refractive index higher than that of cladding, the phase matching condition of the LPG would no longer be valid. The cladding mode in the cladding region would experience both Fresnel reflection and Fresnel refraction. Any major variation in the refractive index would only result in change in the coupling strength, and not the resonance wavelength [9]. More energy would be propagating towards the external medium if the LPG was bent resulting in the change in the LPGs resonance dip with bending curvature [8].

To minimize the risk of trapping water between the layers, after removal from the freezer, the carbon–fiber composite prepegs were left under room temperature for at least 24 h. Having water molecules trapped between the layers would degrade the strength, durability and sensitivity of the sensor.

The overall shape design of the carbon–fiber composite laminate was trapezoidal rather than rectangular because of the structural simulation by using JL analyzer (Auto-FEA Engineering Software Technology, Inc.). Through the simulation results as shown in Fig. 2 it was found that the stress experienced at the trapezoidal structure, where the LPG was positioned, was more widely distributed than the rectangular counterparts, which meant that the ELPG would experience a more uniform bending. A comparison was also made between the simulation results on the cantilever 2-point bending and the 3-point bending, which the latter technique was adopted in this experiment. Comparison shows that in the cantilever 2-point bending, there is a concentration of stress near to the fix point whereas in the 3-point bending, the stress is located at the center of the trapezoidal structure, where the LPG is located. Therefore, to ensure uniform stress distribution on the LPG, 3-point bending would be preferred. Uniform bending on the ELPG is important and if two point bending is to be adapted, chirping of the ELPG will occur [10]. The prototype version of the ELPG is shown in Fig. 3.

Once the embedding process was done, the carbon–fiber composite laminate with the embedded LPG was then transferred to the vacuum oven (Salvis Lab Vacucenter)

for curing. The laminate was cured in a vacuum oven 120 °C for 60 min, according to manufacturer's specifications. The transmission spectrum after the embedding process is shown in Fig. 4. Comparing Figs. 1 and 4, it can be observed that the LPGs transmission dip changed the depth of the resonance dip after the embedding process. As the LPG was previously annealed at temperature 85 °C, which was below than that of the curing process, the high temperature of curing would modify the LPGs coupling strength, which affected the depth of the resonance dip. Study on the transmission characteristics of the LPG showed that the depth of the resonance dip followed a sinusoidal function of the amplitude of the index modulation in the fiber core, which changed during and after UV irradiation and after annealing process [11]. After removing the carbon–fiber composite from the curing plates, the ELPG spectral response for bending was ready to be investigated.

3. Experimental results and discussion

Prior to the gain flattening by the ELPG, the broadband gain spectra of a gain-tunable EDFA (Opto-link EDFAMP with fabrication specification of the pump current from 63 mA to 384 mA) at different pump currents were investigated. The EDFA functioned as a broad-band light source with an uneven spectrum, and the OSA was connected with its output directly to detect its gain spectra. From the well-known relationship between the EDFA gain spectral intensity and the pump current with the increase of the pump current, more erbium ions were involved in the process of amplified spontaneous emission (ASE), so the gain spectral intensity of the EDFA went up correspondingly; in the meantime, the peak amplitude of the EDFA gain spectra increased from -23 to 0 dBm around the wavelength of 1530 nm, followed by that the peak-to-peak ripple of these uneven gain spectra varied between 2 dB and 9 dB. Therefore, by tuning the pump current, an appropriated EDFA gain profile with the corresponding peak-to-peak ripple could be preset for the following gain equalizing experiments.

Next, the transmission spectra of the fabricated ELPG with variable bending were measured. A test jig was designed and manufactured to provide a test platform for the ELPG. As shown in Fig. 5, a micrometer (Newport SM Series Vernier Micrometers), which was attached to the test jig, was used to induce the bending force on the ELPG.

As the experiment was conduced in the laboratory condition, the laboratory temperature was maintained at 22.5 °C. One end of the ELPG was connected to the OSA, while the other end was connected to the TLS. Readings were taken at a stepwise fashion of 0.10 mm depth, h. The radius R of the arc of ELPG under bending is calculated based on the following expression:

$$R = \frac{\left(\frac{d}{2}\right)^2 + h^2}{2h} \tag{1}$$

where d is the distance between two unmovable blocks, which was 80 mm in the bending setup, as shown in Fig. 5. Thus the curvature C is given by

$$C = \frac{1}{R} \tag{2}$$

This curvature would be used as the measurement for the amount of bending the ELPG underwent rather than the depth of the micrometer.

By tuning the micrometer, the ELPG was bent step by step and the transmission spectra of ELPG versus micrometer depth h from 0 to 1.2 mm, or the bending in the term of curvature C from 0 m^{-1} to 1.6 m^{-1}, are displayed in Fig. 6. It could be seen that the resonant peak's amplitude was quite sensitive to the bending. The dip depth of the ELPG dropped gradually with the increase of the bending force. A small resonance wavelength drift of 0.3 nm in the ELPG spectra was observed during the bending, which could be due to the sensitivity of the ELPG to the environmental temperature and the probably induced stretch by the design of the jig setup.

Furthermore, comparing with the EDFA gain ripples, it is found that the ELPG device was capable of tuning the maximum attenuation between approximately -5 and -21 dB while the resonance wavelength of the ELPG kept relatively stable around 1530 nm. Therefore, the manufactured ELPG showed a feasibility to equalize the EDFA gain spectra in the probe.

In the experiment, the ELPG was inserted in cascade behind the EDFA broadband light source while the other end of the ELPG was still connected with the OSA. When the input light from the EDFA passed through the ELPG, due to the diverse transmitted response of ELPG at various wavelengths, the output light decayed variously with wavelength correspondingly. In this case, the ELPG worked as a notch filter and the uneven gain spectrum of the EDFA was compensated by the ELPGs transmission spectrum. The ELPG was bent by tuning the micrometer in the jig, and the dip of transmitted spectra of the ELPG would change correspondingly. Adjusting both the EDFA pump current and ELPG bending curvature, when the peak amplitude of the input gain spectrum of the EDFA and the attenuation of the ELPG canceled well, the output gain spectrum was equalized, and the output result could be detected by the OSA.

When the pump current of the EDFA was 100 mA, the desired equalizing spectrum was the exactly inverted EDFA gain spectrum as shown in Fig. 7. As the bending curvature of the ELPG was 1.51 m^{-1}, the practical ELPG spectrum was most close to the desired one, and finally, the flattening result of the EDFA gain spectrum is illustrated in Fig. 8. The central wavelengths of EDFA gain peak and ELPG transmission dip were 1531.05 and 1530.80 nm, respectively. After the compensation, 1 dB ripple with a 34 nm bandwidth from 1527.1 nm to 1561.1 nm was achieved.

Moreover, the configuration also demonstrated a potential of dynamic attenuation control ability. The fluctuated amplitude of the EDFA gain peak at different pump current

can be compensated by bending the ELPG. From the experimental results shown in Fig. 9, it was found that when using the well-designed ELPG as a spectral equalizer, it reduced the peak-to-peak ripple in the EDFA gain spectrum below 2 dB while the pump current went up from 80 mA to 200 mA, with the flattening region of 32 nm.

4. Conclusion

A novel tuning technology by using bending long period grating (LPG) embedded in carbon–fiber composite laminates or so-called ELPG for erbium doped fiber amplifier (EDFA) gain flattening is proposed. From the experimental results, this compensation method is proven simple and feasible. After compensating, the flatten gain region can achieve beyond 34 nm with a 1 dB fluctuation. Furthermore, the configuration also demonstrates a potential of dynamic attenuation control ability in some special applications.

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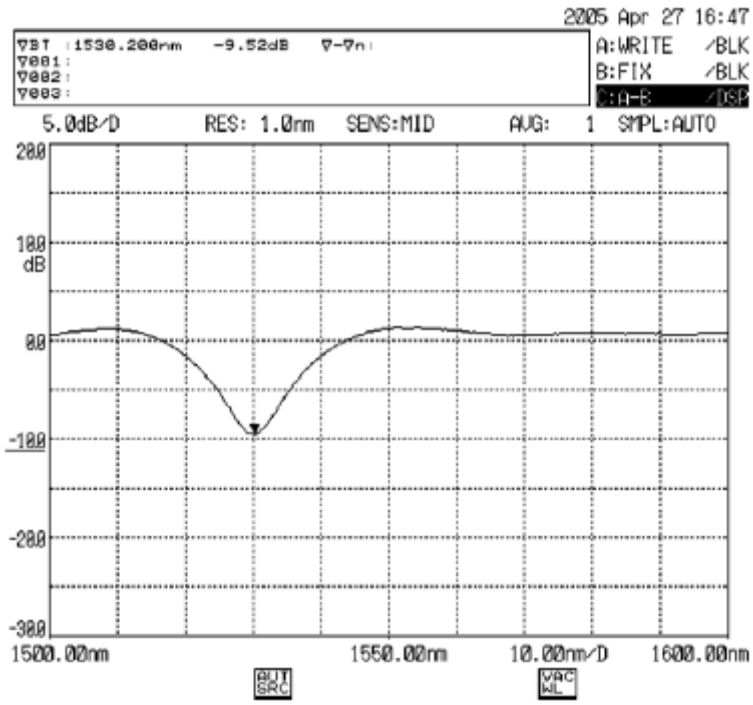
Fig. 9 Dynamic flattening results when the pump power of the EDFA was 200 mA, 100 mA and 80 mA, respectively.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▽002:
▽003:
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C:A-B /DSP
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SENS:MID
AVG: 1
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100
dB
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1600.00nm
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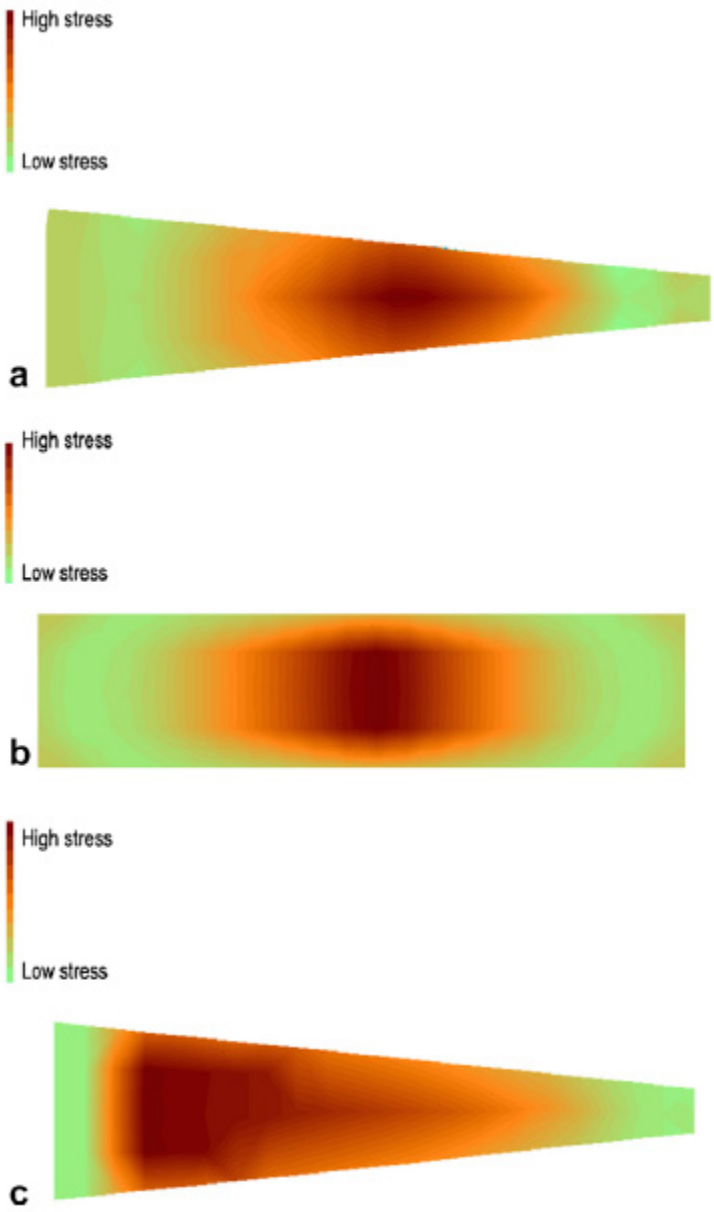
VAC WL

Fig. 1.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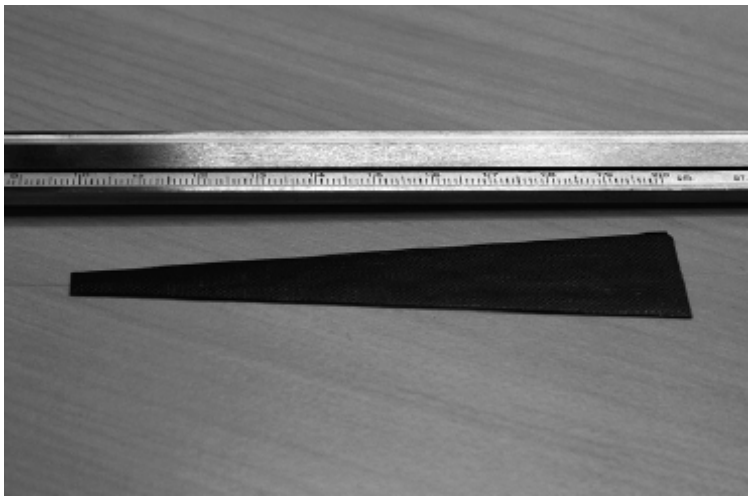
Low stress
a
High stress
Low stress
b
High stress
Low stress
c

Fig. 2.



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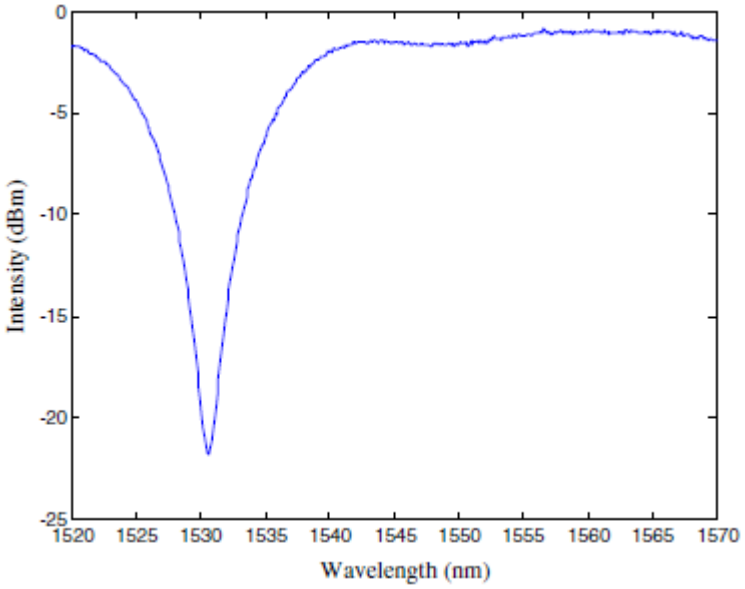
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-5
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-25
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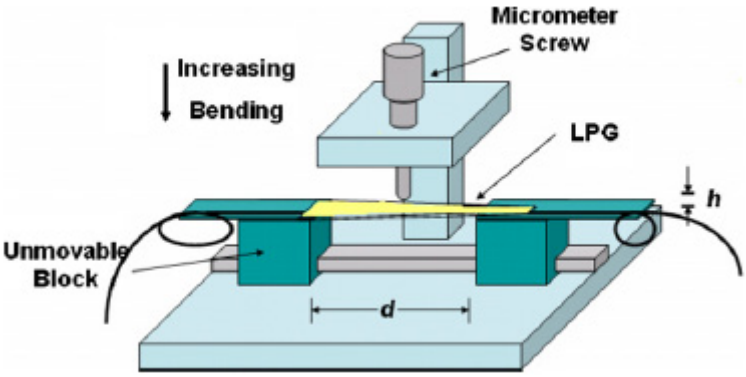
1545
1550
1555
1560
1565
1570
Wavelength (nm)

Fig. 4.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Bending
LPG
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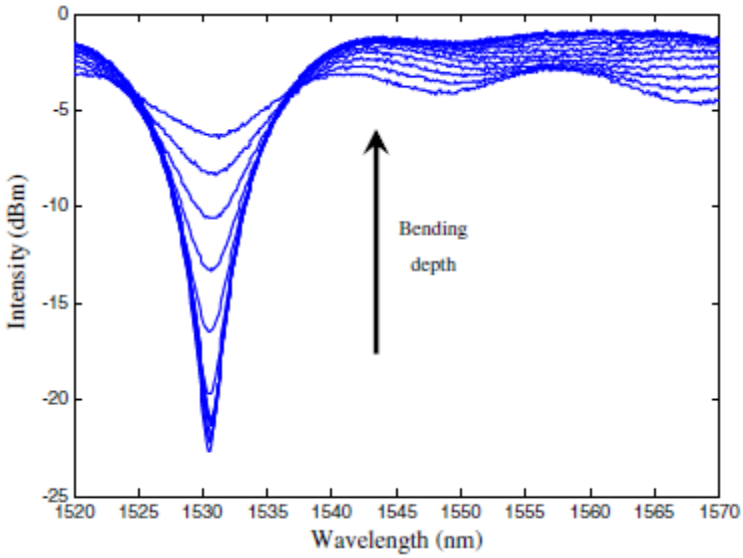
Fig. 5.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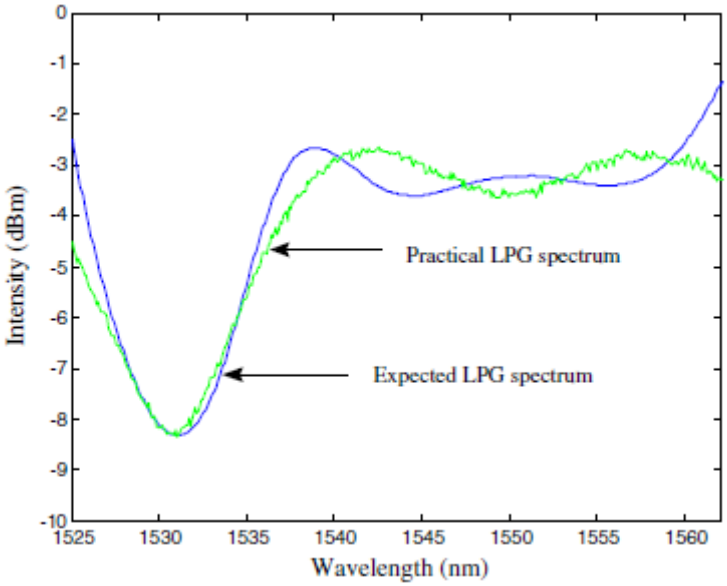
Wavelength (nm)
Bending
depth

Fig. 6.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Intensity (dBm)
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1560
Wavelength (nm)
Practical LPG spectrum
Expected LPG spectrum

Fig. 7.

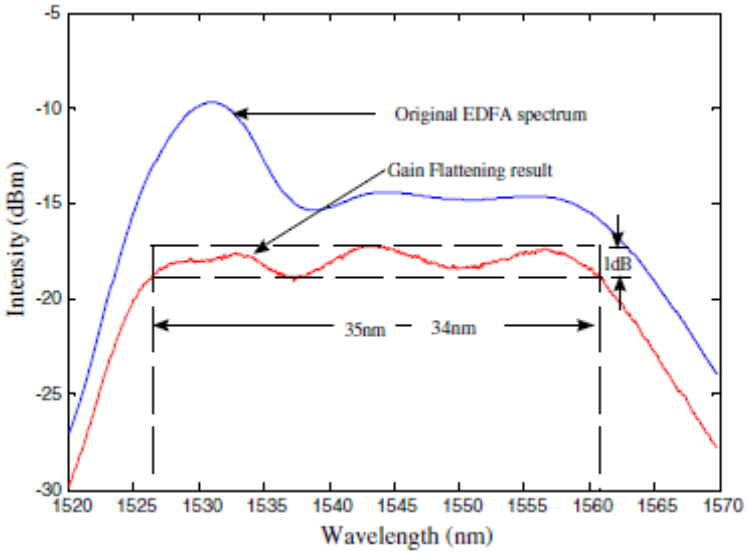
Original EDFA spectrum
Gain Flattening result
1dB
35nm
34nm
Intensity (dBm)
Wavelength (nm)
-5
-10
-15
-20
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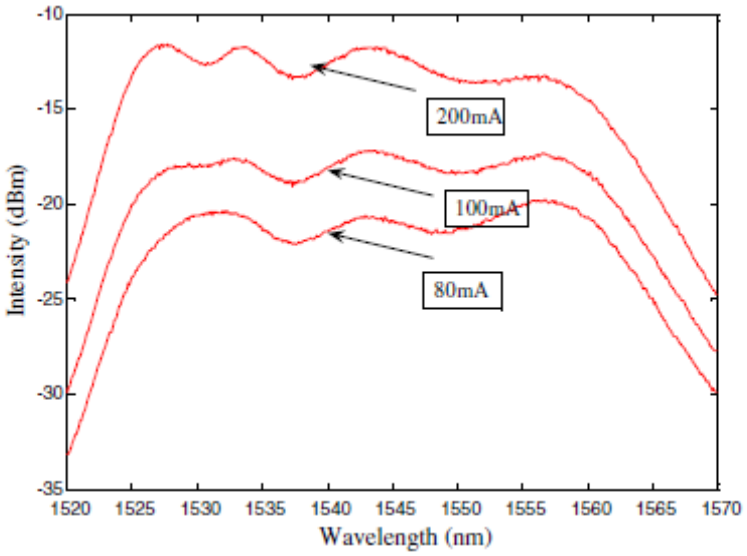
Fig. 8.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-30
-35
Intensity (dBm)
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1525
1530
1535
1540
1545
1550
1555
1560
1565
1570
Wavelength (nm)
200mA
100mA
80mA

Fig. 9.