Performance evaluation of mode-locked erbium-doped fibre lasers in optical sensor networks

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Abstract

The performance of mode-locked erbium-doped fibre lasers in optical sensor networks is analysed and compared with the results obtained by using commercial erbium-doped fibre amplifiers as source. Passive mode-locked lasers developed are based on nonlinear polarization rotation and they have been built using the same erbium-doped fibre amplifiers. To simulate a real sensor network, a tree structure with four fibre Bragg gratings was built by employing 50/50 couplers. The mode-locked laser developed offers a reasonably good behaviour at a very wide spectral range (82 nm, approximately) over C and L bands. The signal to noise ratio and the peak power are greatly improved with regard to the values obtained employing commercial amplifiers as source.

Keywords: optical network, fibre Bragg grating, mode-locked laser, erbium-doped fibre, nonlinear polarization rotation.

1 Introduction

Nowadays, optical sensor networks based in fibre Bragg gratings (FBGs) could be used in a great number of applications provided that a suitable optical source is selected. An excellent choice would be use a laser for every FGB, since unbeatable results could be obtained as long as both are tuned. However, it can be necessary to tune them by means of some dynamical procedure since as laser wavelengths as FBG wavelengths depend on the temperature and therefore this kind of networks can result too expensive and complicate. Another cheaper option should be based on the use of a multiwavelength laser as source, although the signal to noise ratio (SNR) is usually deteriorated and laser wavelengths should be individually tuned for every FBG. Furthermore, the spectral range is limited (around 40 nm) because these sources are made employing an erbium-doped fibre amplifier (EDFA) or a semiconductor optical amplifier (SOA) as active medium. Evidently, a spectrally wide and powerful source would be the cheapest and the simplest option. However, this kind of source is not available, since the SNR and the spectral power are too low, even employing the amplified spontaneous emission (ASE) power emitted by commercial EDFAs.

A suitable solution could be use a pulsed erbium-doped fibre laser (EDFL) by means of some mode-locking technique. If the laser power is post-amplified by an EDFA, then the laser power offers a very wide spectrum and a mean power high enough. In this paper, the performance of sensor networks with this kind of source is analysed and compared with the results obtained by using the same EDFAs as ASE sources. Concretely, passive mode-locked lasers based on nonlinear polarization rotation (NPR) have been developed using a commercial EDFA in L-band as active medium and another second commercial EDFA in C-band as post-amplifier. Moreover, both EDFAs are also swapped in order to check the results provided by this second pulsed source. Only commercial EDFAs have been used because they can be usually found at an optical fibre laboratory. Furthermore, it is necessary to point out that neither the chromatic dispersion of the laser cavity is compensated nor the pulse duration is optimized. Accordingly, although the optimisation of picoseconds pulses was not possible due to the lack of specific compensation devices, these sources could be easily developed.

2 Material and Methods

As it can be seen in Figs. 1 and 2, several setups were made to analyse the best SNR. Spectral power measurements were done by means of an optical spectrum analyser (OSA, Agilent, model 86142B), employing different values of resolution (0.06 nm, 0.1 nm, 0.5 nm, and 1 nm). As it was expected, the lower resolution, the better signal to noise ratio. And obviously, the greater resolution, the higher output power.

To simulate a real sensor network, a tree structure with four FBGs was built by employing 50/50 couplers. Each FBG reflects around a different wavelength and the four wavelengths are separated enough in order to span a very wide spectral range (82 nm, approximately) over C and L bands. Concretely, selected wavelengths are: 1529.77 nm ($\Delta\lambda$ = 0.16 nm, Chylas), 1560.00 nm ($\Delta\lambda$ = 0.17 nm, Chylas), 1588.73 nm ($\Delta\lambda$ = 0.25 nm, Technica) and 1611.64 nm ($\Delta\lambda$ = 0.25 nm, Technica).

Thus, SNR measurements of the two configurations were compared. In Fig. 1, the source and the sensor network are together and the OSA is placed in a far point. A fibre spool of 7.6 Km length (LS-LEAF, Corning) is used to simulate the effect of acting in a far point Therefore, the distance between sensors and OSA can be 7.6 Km (Fig. 1a) or 15.2 Km (Fig. 1b), including an optical circulator and an all-fibre mirror in the setup. Moreover, an optical isolator is placed before the gratings in order to avoid undesired reflections toward the source. In Fig. 2, the OSA is near the source and both are far away from the sensor network.

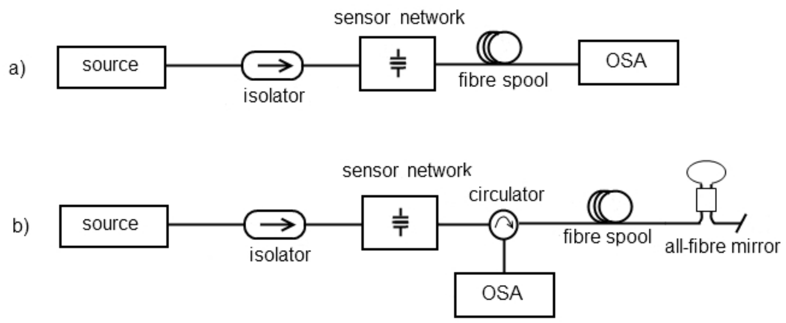

Figure 1. Experimental setup assuming that the source and the sensor network are together and the OSA is in a far point.

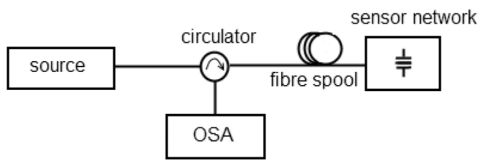

Figure 2. Experimental setup considering that the OSA is near the source and both are far away from the sensor network.

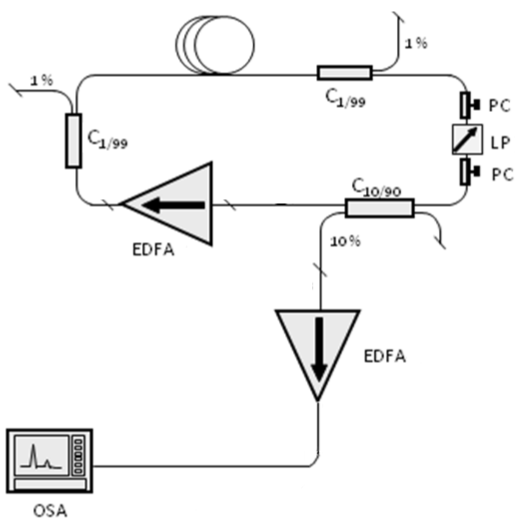

Figure 3. Scheme of the pulsed laser developed.

These setups were evaluated for several kinds of source, but working always with two commercial EDFAs. The first EDFA (Highwave, model C20-G20-H-FC/APC-BTO 3.0, 20 dBm output saturation power), henceforth EDFA-C, operates in the C-band (from 1525 nm to 1565 nm, approximately). The second EDFA (Keopsys, model KPS-BT2-L-20-PB-FA, 20 dBm output saturation power), henceforward EDFA-L, operates in the L-band (from 1570 nm to 1610 nm, approximately). Thus, the following sources were built: 1) the ASE power of the

EDFA-C, 2) the ASE power of the EDFA-L, 3) the ASE power of the EDFA-C amplified by the EDFA-L, 4) the ASE power of the EDFA-L amplified by the EDFA-C, 5) mode-locked pulses (with EDFA-C as active medium) amplified by the EDFA-L, and 6) mode-locked pulses (with EDFA-L as active medium) amplified by the EDFA-C.

The scheme of mode-locked lasers developed is shown in Fig. 3. The passive mode-locking is based on NPR and it is necessary to insert a linear polarizer between two polarization controllers. Although the ring cavity has several outputs, only the 10% output was used in this study. Finally, laser pulses are amplified by a second EDFA. The mean spectral power obtained is gathered in Figs. 4 and 5.

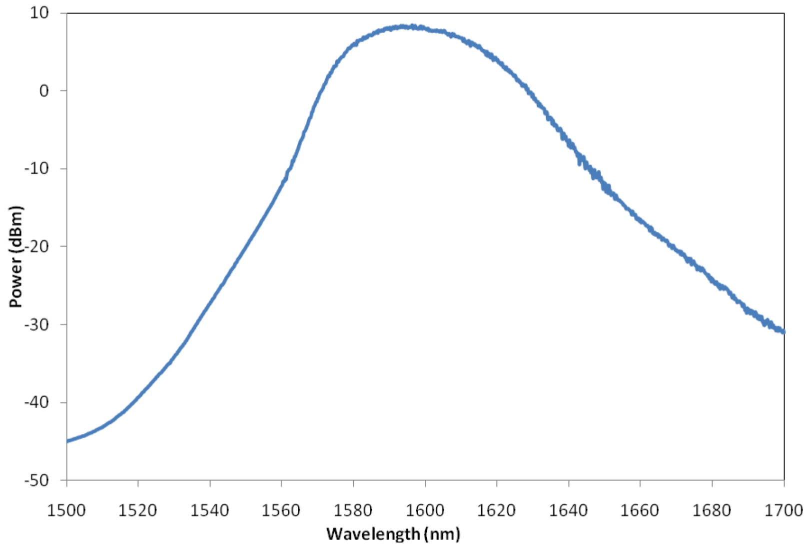

Figure 4. Spectral power emitted by the mode-locked laser with the EDFA-C as active medium and the EDFA-L as post-amplifier. The OSA resolution is 1 nm.

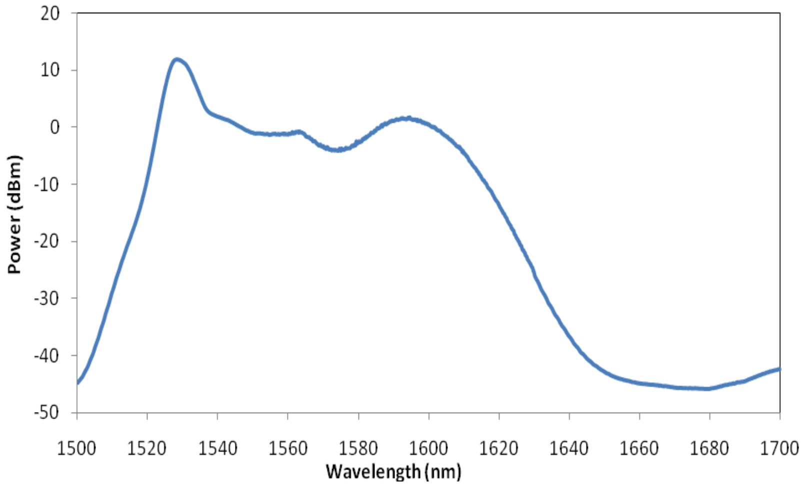

Figure 5. Spectral power emitted by the mode-locked laser with the EDFA-L as active medium and the EDFA-C as post-amplifier. The OSA resolution is 1 nm.

3 Results

Spectral power measurements obtained for the experimental setup of Fig. 1 (the source and the sensor network are together and the OSA is in a far point) employing the ASE power of the EDFA-C, the ASE power of the EDFA-C amplified by the EDFA-L, mode-locked pulses amplified by the EDFA-L, and mode-locked pulses amplified by the EDFA-C are shown in Figs. 6, 7, 8, and 9, respectively. Moreover, values of SNR and peak power at the four wavelengths selected by FBGs are compared in Table 1. The results with double spool are not shown because are very similar to the simple spool.

Taking into account the results at the four wavelengths, the ring-L+EDFA C source offers the best behaviour, since both the peak power and the SNR are clearly better, as it can be appreciated in Table 1. Other sources offer a SNR very poor (lower than 10 dB) or a peak power very low (lower than -45 dBm) at some of the four wavelengths. Nevertheless, if only the two longer wavelengths were considered, then the ring-C+EDFA-L source would be lightly better, since it provides a higher peak power at these wavelengths.

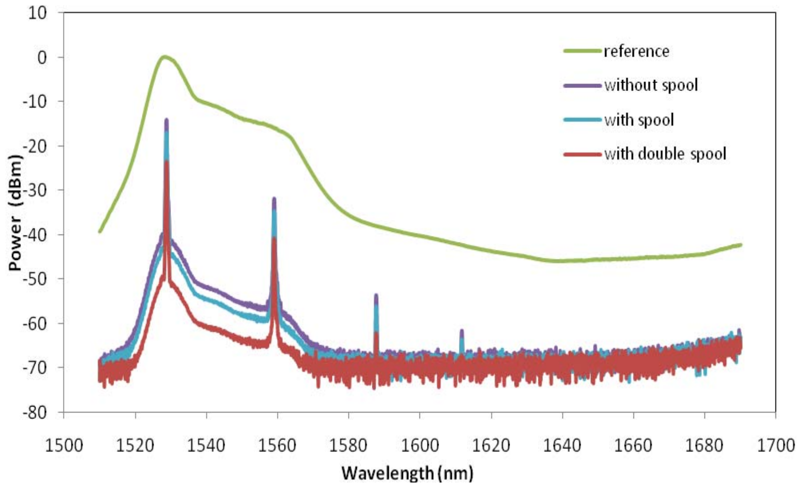

Figure 6. Spectral power measurements obtained for the setup of Fig. 1 employing the ASE power of the EDFA-C (resolution of 0.06 nm).

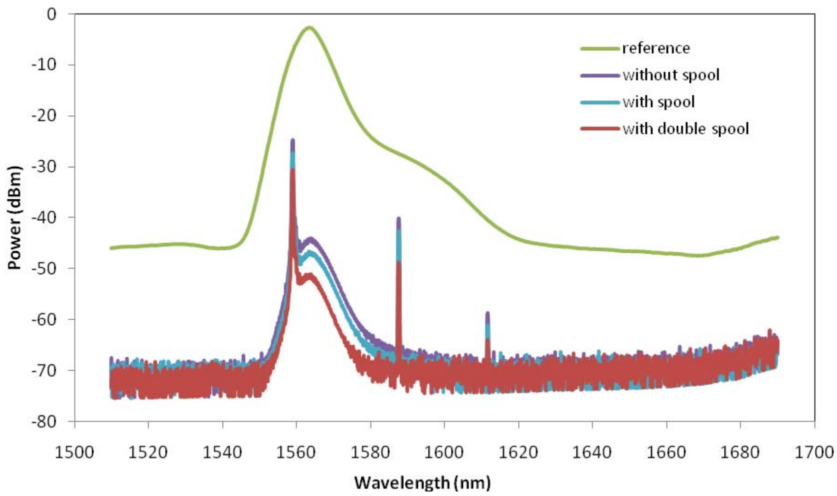

Figure 7. Spectral power measurements obtained for the setup of Fig. 1 employing the ASE power of the EDFA-C amplified by the EDFA-L (resolution of 0.06 nm).

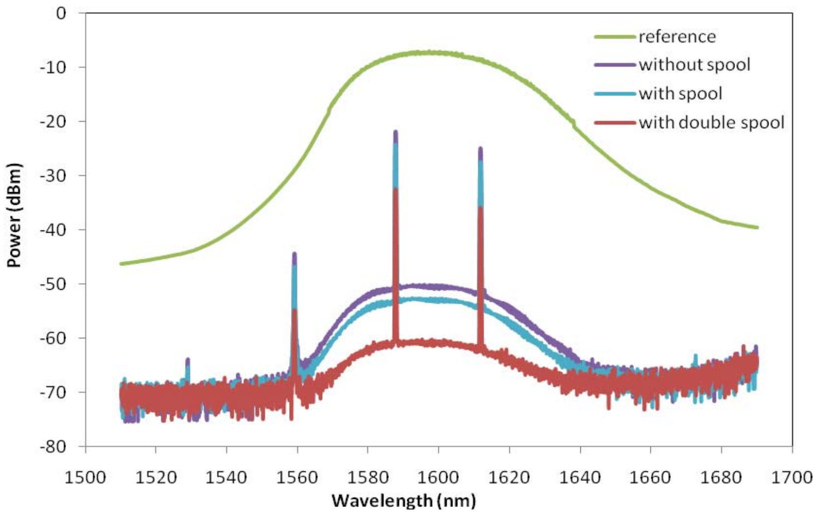

Figure 8. Spectral power measurements obtained for the setup of Fig. 1 employing mode-locked pulses amplified by the EDFA-L (resolution of 0.06 nm).

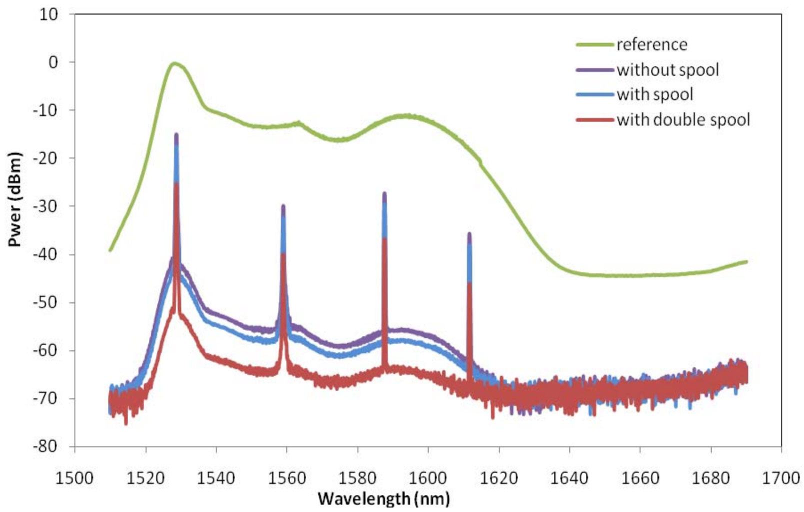

Figure 9. Spectral power measurements obtained for the setup of Fig. 1 employing mode-locked pulses amplified by the EDFA-C (resolution of 0.06 nm).

Source	*EDFA C*	*EDFA C- EDFA L*	*ring C-EDFA L*	*ring L-EDFA C*
Wavelength (nm)	*SNR (dB) without/with spool*	*SNR (dB) without/with spool*	*SNR (dB) without/with spool*	*SNR (dB) without/with spool*
1528.78	26.87/26.95	1.38/1.00	7.48/5.32	**27.06/26.89**
1559.02	22.56/22.14	20.00/19.77	19.97/20.03	**21.68/21.77**
1587.64	14.15/12.17	27.36/26.04	**28.23/28.34**	**28.49/28.02**
1611.64	8.03/5.02	9.70/11.25	**26.06/26.80**	**26.83/26.00**

Source	*EDFA C*	*EDFA C- EDFA L*	*ring C-EDFA L*	*ring L-EDFA C*
Wavelength (nm)	*Max. power (dBm) without/with spool*	*Max. power (dBm) without/with spool*	*Max. power (dBm) without/with spool*	*Max. power (dBm) without/with spool*
1528.78	-14.08/-16.92	-68.83/-68.90	-63.96/-65.64	**-15.04/-17.53**
1559.02	-31.82/-34.59	-24.65/-27.25	-44.36/-46.74	**-29.89/-32.39**
1587.64	-53.53/-56.08	-40.04/-42.56	**-21.88/-24.24**	**-27.27/-29.62**
1611.64	-61.65/-63.52	-58.68/-60.96	**-24.99/-27.44**	**-35.65/-38.12**

Table 1. Signal to noise ratio and peak power measured with a resolution of 0.06 nm employing the following sources: the ASE power of the EDFA-C (EDFA-C), the ASE power of the EDFA-C amplified by the EDFA-L (EDFA-C+EDFA-L), mode-locked pulses amplified by the EDFA-L (ring-C+EDFA-L) and mode-locked pulses amplified by the EDFA-C (ring-L+EDFA-C).

Spectral power measurements obtained for the experimental setup of Fig. 2 (the OSA is near the source and both are far away from the sensor network) are also shown in Figs. 10, 11, 12, and 13. Moreover, values of SNR and peak power at the four wavelengths selected by FBGs are compared in Table 2. The four sources compared now are: the ASE power of the EDFA-L, the ASE power of the EDFA-L amplified by the EDFA-C, mode-locked pulses amplified by the EDFA-L, and mode-locked pulses amplified by the EDFA-C.

Taking into account the results at the four wavelengths, the ring-L+EDFA C source again offers the best behaviour, since both the peak power and the SNR are clearly better, as it can be appreciated in Table 2. Other sources offer a SNR very poor (lower than 10 dB) or a peak power very low (lower than -45 dBm) at some of the four wavelengths. Nevertheless, if only the two longer wavelengths were considered, then the ring-C+EDFA-L source would be lightly better, since it provides a higher peak power at these wavelengths.

Moreover, it is very important to note that SNR results strongly deteriorated if the fibre spool is added, since nonlinear effects are generated by mode-locked pulses as they travel along the fibre spool due to their very high power. However, SNR is only slightly modified if the fibre spool is added in the setup shown in Fig. 1. Therefore, it is greatly advisable to place the source and the sensor network together and the OSA in a far point.

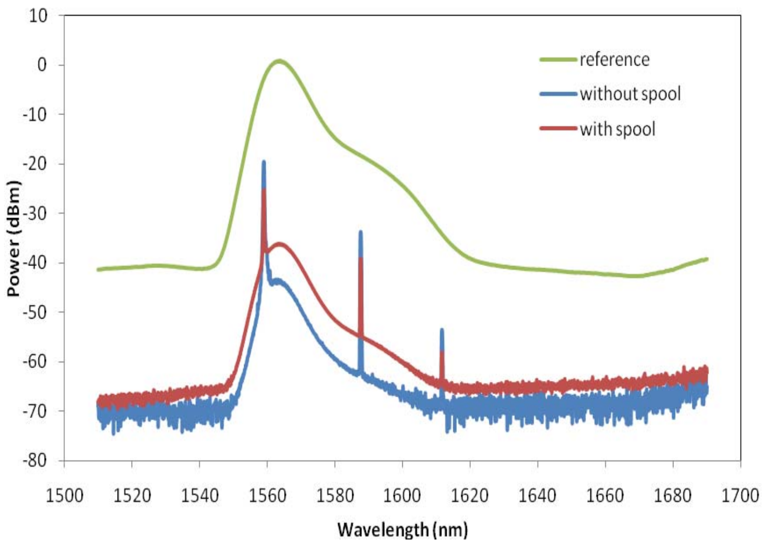

Figure 10. Spectral power measurements obtained for the setup of Fig. 2 employing the ASE power of the EDFA-L (resolution of 0.06 nm).

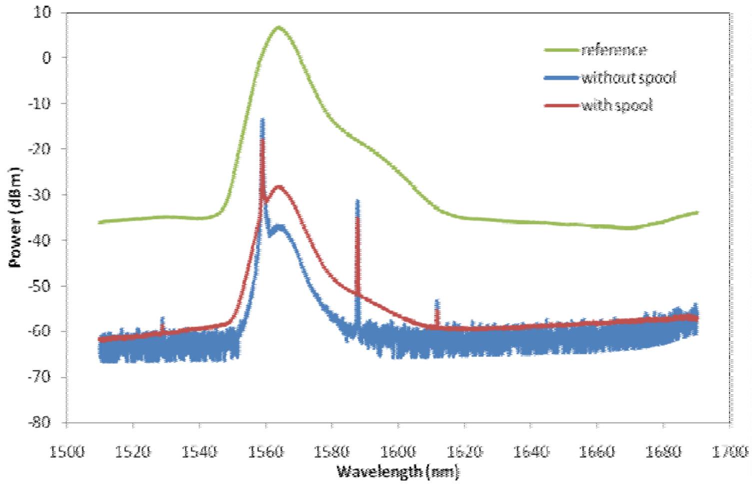

Figure 11. Spectral power measurements obtained for the setup of Fig. 2 employing the ASE power of the EDFA-L amplified by the EDFA-C (resolution of 0.06 nm).

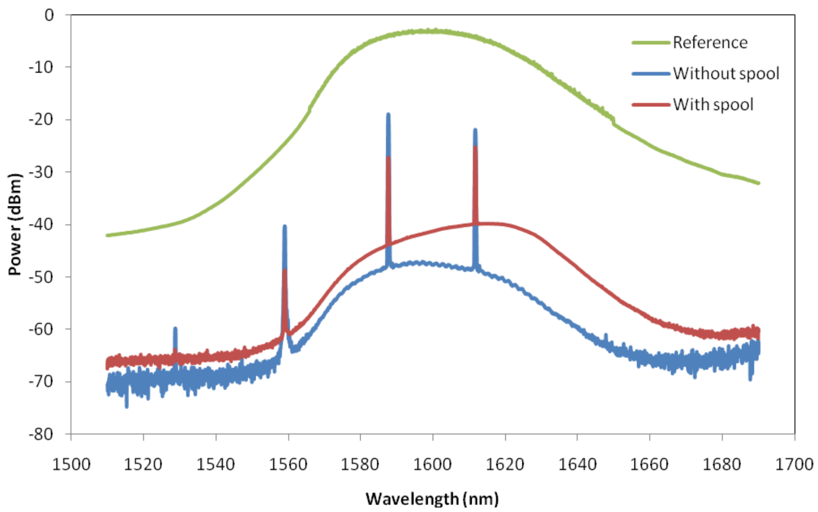

Figure 12. Spectral power measurements obtained for the setup of Fig. 2 employing mode-locked pulses amplified by the EDFA-L (resolution of 0.06 nm).

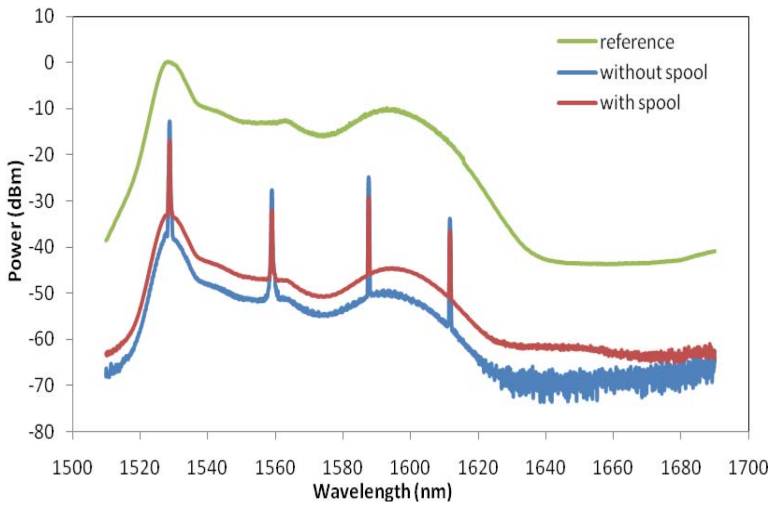

Figure 13. Spectral power measurements obtained for the setup of Fig. 2 employing mode-locked pulses amplified by the EDFA-C (resolution of 0.06 nm).

Source	***EDFA L***	***EDFA L- EDFA C***	***ring C-EDFA L***	***ring L-EDFA C***
Wavelength (nm)	*SNR (dB) without/with spool*	*SNR (dB) without/with spool*	*SNR (dB) without/with spool*	*SNR (dB) without/with spool*
1528.78	1.09/0.72	4.20/1.69	10.49/1.92	**24.98/16.30**
1559.02	20.87/12.61	23.67/13.69	21.55/12.09	**21.00/14.63**
1587.64	28.66/16.02	30.08/16.97	**28.41/16.56**	**25.20/16.54**
1611.64	16.04/6.74	8.36/3.94	**26.56/14.69**	**23.21/14.92**

Source	***EDFA L***	***EDFA L- EDFA C***	***ring C-EDFA L***	***ring L-EDFA C***
Wavelength (nm)	*Max. power (dBm) without/with spool*	*Max. power (dBm) without/with spool*	*Max. power (dBm) without/with spool*	*Max. power (dBm) without/with spool*
1528.78	-67.99/-66.50	-57.07/-58.51	-59.80/-63.90	**-12.77/-16.88**
1559.02	-19.65/-25.20	-13.43/-17.87	-40.31/-48.73	**-27.67/-32.01**
1587.64	-33.80/-39.08	-31.36/-35.06	**-18.92/-27.20**	**-24.89/-29.15**
1611.64	-53.54/-58.07	-53.35/-55.25	**-21.89/-25.21**	**-33.86/-36.47**

Table 2. Signal to noise ratio and peak power measured with a resolution of 0.06 nm employing the following sources: the ASE power of the EDFA-L (EDFA-L), the ASE power of the EDFA-C amplified by the EDFA-L (EDFA-C+EDFA-L), mode-locked pulses amplified by the EDFA-L (ring-C+EDFA-L) and mode-locked pulses amplified by the EDFA-C (ring-L+EDFA-C).

4 Conclusions

The mode-locked laser developed employing two commercial EDFAs (mode-locked pulses are generated by the EDFA-L and amplified by the EDFA-C) offers a reasonably good behaviour at a very wide spectral range (82 nm, approximately) over C and L bands. Moreover, the SNR and the peak power obtained employing these commercial EDFAs as wide source are greatly improved by means of this technique, even although the cavity dispersion is not compensated. Finally, it has been demonstrated that it is preferable to place the source and the sensor network together and the OSA in a far point to avoid nonlinear effects generated by the high power of mode-locked pulses, which deteriorate the SNR. This study should be continued including optical sensors in the network and analysing the behaviour of the SNR. The authors are currently working in this issue.

5 Acknowledgments

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