WDM bi-directional transmission over 35 km amplified fiber-optic bus network using Raman amplification for optical sensors

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Abstract: We demonstrate a novel distributed fiber Raman amplified bus topology used for WDM transmission over 35 km of single-mode fiber by use of a multiwavelength Raman pump laser and eight Fiber Bragg gratings (FBGs). This topology reduces the number of addressing wavelengths needed at the head of the bus. Furthermore, by relocating the FBGs' wavelengths of a first section, it is obtained power transparency at the end of the overall bus, without requiring any additional pump source. We show how the topology allows the received powers from the first section sensors to be equalized and partially amplify the overall network. We investigate how the performance depends on the launched pump power. Results obtained with this new configuration are compared with those achieved in a previously reported optically amplified bus topology.

OCIS codes: (060.2370) Fiber optics sensors; (140.3550) Lasers, Raman; (060.4230) Multiplexing; (050.2770) Gratings.

References and links

1. R. Hernández-Lorenzo, M. López-Amo, and P. Urquhart, "Single and double distributed optical amplifier fiber bus networks with wavelength division multiplexing for photonic sensors," J. Lightwave Technol. **16**, 485-489 (1998).
2. A. Dandridge, and C. Kirkendell, "Passive fiber optic sensor networks" in *Handbook of Optical Fiber Sensing Technology*, J. M. López-Higuera, ed. (John Wiley, 2002), Chap. 21.
3. P. E. Green, *Fiber Optic Networks,* Englewood Cliffs, ed. (NJ: Prentice Hall, 1992), 357-369.
4. L. T. Blair and S. A. Cassidy, "Wavelength division multiplexed sensor network using Bragg fiber reflection gratings," Electron. Lett. **28**, 1734-1735 (1992).
5. B. Vizoso, I. R. Matías, M. López-Amo, M. A. Muriel, and J. M. López-Higuera, "Design and application of double amplified recirculating ring structure for hybrid fiber buses," Opt. Quantum Electron. **27**, 847-857 (1995).
6. M. López-Amo, L. T. Blair, and P. Urquhart, "Wavelength-division multiplexed distributed optical fiber amplifier bus network for data and sensors," Opt. Lett. **18**, 1159-1161 (1993).
7. J. D. Ania-Castañón, "Quasi-lossless transmission using second-order Raman amplification and fibre Bragg gratings," Opt. Express **12**, 4372-4377 (2004). http://www.opticsexpress.org/abstract.cfm?URI=OPEX-12-19-4372
8. T. J. Ellingham, J. D. Ania-Castañón, S. K. Turitsyn, A. Pustovskikh, S. Kobtsev, and M. P. Fedoruk, "Dual-pump Raman amplification with increased flatness using modulation instability," Opt. Express **13**, 1079-1084 (2005). http://www.opticsexpress.org/abstract.cfm?URI=OPEX-13-4-1079
9. J. H. Lee, Y. M. Chang, Y. G. Han, et al., "Raman amplifier-based long-distance remote, strain and temperature sensing system using an Erbium-Doped Fiber and a Fiber Bragg Grating, " Opt. Express **12**, 3515-3520 (2004). http://www.opticsexpress.org/abstract.cfm?URI=OPEX-12-15-3515
10. Y. Emori, K. Tanaka, and S. Namiki, "100nm bandwidth flat-gain Raman amplifiers pumped and gain-equalised by 12-wavelength-channel WDM laser diode unit," Electron. Lett. 1355-1356 (1999).
11. S. Diaz, G. Lasheras, M. López-Amo, P. Urquhart, C. Jáuregui, and J. M. López-Higuera, "Wavelength-division-multiplexed distributed fiber raman amplifier bus network for sensors", in *Proc. 17th Int. Conf. Optical Fibre Sensors (OFS-17),* Proc. SPIE 5855, 242-244 (2005).

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12. S. Diaz, G. Lasheras, P. Urquhart, C. Jáuregui, J. M. López-Higuera, and M. López-Amo, "Improved distributed fiber raman amplifier bus network with wavelength division multiplexing for sensors,"(to be published).
13. J. Bromage, P. J. Winzer, and R. J. Essiambre, “Multiple path interference and its impact on system design”, in *Raman Amplifiers for Telecommunications 2*, M. N. Islam ed. (Springer, 2004), Chap. 15.
14. L. Grüner-Nielsen and Y. Qian, “Dispersion-compensating fibers for Raman applications”, in *Raman Amplifiers for Telecommunications 1*, M. N. Islam ed. (Springer, 2004), Chap. 6.
15. P. B. Hansen, G. Jacobovitz-Veselka, L. Grüner-Nielsen, and A. J. Stentz, “Raman amplification for loss compensation in dispersion compensating fibre modules” Electron. Lett. **34**, 1136-1137 (1998).
16. Y. Emori, Y. Akasaka, and S. Namiki, “Broadband lossless DCF using Raman amplification pumped by multichannel WDM laser diodes”, Electron. Lett. **34**, 2145-2146 (1998).
17. A. H. Gnauck, G. Raybon, S. Chandrasekhar, J. Leuthold, et al., “2.5 Tb/s (64 x 42.7 Gb/s) Transmission over 40 x 100 km NZDSF using RZ-DPSK format and all-Raman-amplified spans”, in *Proc. of OFC’02*, (Anaheim, Calif., 2002), pp. FC2-1-FC2-3.
18. B. Zhu, L. Leng, L. E. Nelson, et al., “3.2 Tb/s (80 x 42.7 Gb/s) Transmission over 20 x 100 km of non-zero dispersion fibre with simultaneous C + L-band dispersion compensation”, in *Proc. of OFC’02*, (Anaheim, Calif., 2002), pp. FC8-1-FC8-3.

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1. Introduction

Optical fiber bus architectures are highly desirable for both sensing and telecommunications applications [1-4]. They have simple cabling requirements compared to star and fully interconnected networks and they potentially provide a means to increase the degree of integration of different types of data traffic. However, fiber bus networks suffer the disadvantage that signals addressing remote stations must pass through numerous directional couplers and thus experience severe attenuation. Optical amplification in both lumped [3], [5] and distributed [6] formats has been demonstrated as a good solution to the problem. Distributed amplification is particularly appealing, due to the need for a single pump source for all of the structure, reducing the network’s cost and complexity.

Recent years have seen an increase in the use of distributed Raman amplification in optical fiber transmission links, thanks to the availability of powerful Raman pumps [7]. The capacity of wavelength-division-multiplexed (WDM) systems is limited by the gain bandwidth of erbium-doped fiber amplifiers (EDFAs). Multiple-pump fiber Raman amplifiers (FRAs) can increase the transmission bandwidth. Moreover, Raman amplifiers have better noise performance than EDFAs because the amplification is distributed.

The application of distributed Raman amplification in long-haul, broadband transmission using wavelength division multiplexing (WDM) relies on the ability of the amplifiers to provide a flat gain profile to enable maximum reach of all signal channels [8-9]. The gain flatness of the amplifier over its operational bandwidth can be improved by using a large number of pumps [10].

In this work, we propose a novel network scheme that combines the use of a multiwavelength Raman pump laser and eight Fiber Bragg gratings (FBGs) for WDM transmission over single-mode fiber; reducing simultaneously the number of wavelengths for addressing the sensors. This network is an evolution of a previously reported Raman bus structure that provides power transparency (constant optical power throughout the whole optical path) and yields equalized received powers from a number of independent sensors [11].

2. Experimental results

The original setup was the bus topology shown in Fig. 1(a) [11], with an active bus built on standard single-mode fiber (ITU-G.652 compliant). This setup was used for wavelength-division multiplexing (WDM) four sensors. Each sensor incorporates a narrow-bandwidth FBG at a unique wavelength. The launched signals are ultimately incident on all of the sensors but the gratings ensure that each sensor returns only its characteristic channel towards the launching point (the head end) after passing through the sensor a second time.

In this new demonstration, the sensors were removed in order to make the power measurements independent of the particular measurands and so ensure greater generality of the results. Thus, the network is not designed to be specific to any particular type of sensor. The Raman pump and signal(s) are co-located in one head end. The Raman pump propagates co-directionally with the launched signal but contra-directionally with the reflected signals from the gratings. The couplers shown in Fig. 1 had coupling ratios of 90:10 at the pump and signal wavelengths. All of the free terminations on the bus were refractive-index-matched to frustrate unwanted reflections. This is necessary to minimize multi-path interference [13].

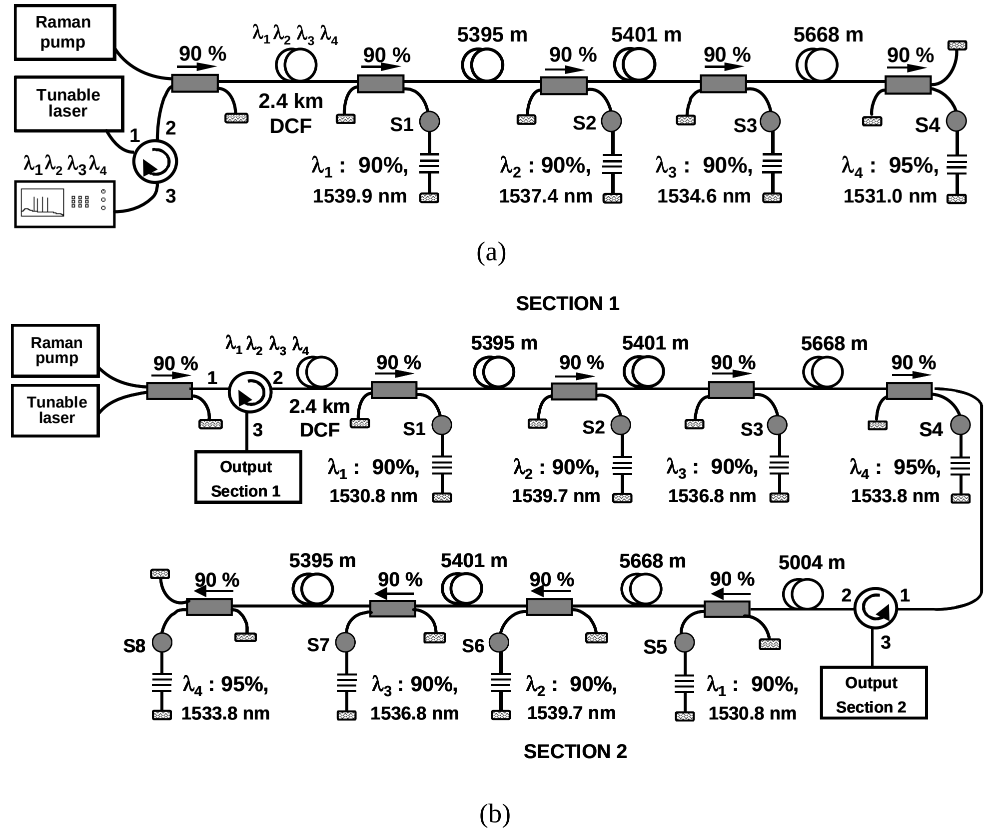

Fig. 1. (a) Original wavelength-division-multiplexed distributed fiber Raman amplifier bus network. S1-S4 location of sensors. (b) New distributed fiber Raman amplifier bus network adding 4 sensors. S1-S8 location of sensors. The fiber lengths and the grating peak wavelengths and reflectivities are indicated.

The Raman pump laser was a multiwavelength Raman pump laser and it launched three pump wavelengths: 1428 nm, 1445 nm and 1466 nm. It could deliver up to 2W power into the single-mode fiber. In the setup of Fig. 1 the signal was provided by a tunable laser (1460-1580 nm) and it had a spectral linewidth of 5 MHz and a power of -1.5 dBm in both cases. The launched pump was polarization scrambled but there was a small residual elliptical polarization of the signal laser. By taking multiple measurements, +/- 0.5 dB errors are estimated in the measured gain values.

The peak wavelengths and reflectivities of the gratings are included on Fig. 1. They had a wavelength variation with temperature of 0.01 nm/ºC, but they have been stabilized in this

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experiment in temperature. As shown in Ref. [12], by adding the 2.4 km DCF there is enough distance to obtain Raman gain for every grating, even for the one closest to the pump. We used this property to obtain a degree of equalization of the received powers from the four gratings. In the case of Fig. 1(a), the strategy was to place the gratings corresponding to low Raman gains closest to the pump because that is where the signals experience enough amplification. Conversely, gratings with relatively high Raman gain wavelengths were located further from the head end.

From Ref. [14], it is known that Raman amplification is oriented to long-distance bus networks. Therefore, the span of 2.4 km of dispersion compensating fiber (DCF) of the original configuration was added in order to compensate 20 km of standard single mode fiber (SMF), and to maximize the Raman gain in the head end of the bus. In fact, 2.4 km of DCF are equivalent to 20 km of G.652 fiber.

Dispersion compensating fibers (DCF) are used as a Raman gain medium for dispersion compensation [14-15]. A broadband lossless DCF using multiple-wavelength Raman pumping was demonstrated by Emori et al. [16]. The main characteristic of the DCF is its relatively high germanium doping level and its small effective area. In Refs. [17-18] was demonstrated a combination of Raman amplification in the transmission fiber and dispersion-compensating Raman amplifiers (DCRA) in order to obtain an all-Raman system.

The main objective of the configuration shown in Fig. 1(b) was WDM multiplexing eight sensors saving addressing wavelengths. Thus, we used pairs of Fiber Bragg Gratings with the same wavelength in order to save the half of wavelengths and therefore reducing the wavelengths' source complexity. By adding another circulator to the original scheme, now there are two sections, so that it is possible to relocate the first four section's wavelengths into the other. The two circulators are placed in order to distribute the power along the two sections, and also to measure the received signals at those points (marked in Fig. 1(b) as Output Section 1 and Output Section 2) by means of an optical spectrum analyzer. The two sections follow the same configuration using 90% directional couplers, spans of approximately 5 km standard single-mode fiber and the same four FBGs. So, Fig. 1(b) increases the number of sensors by adding an extra circulator, but with the advantage of the fact that the half of the wavelengths are saved. An additional advantage is that the wavelengths could be relocated to provide power equalization.

We want to prove that by using the three pump wavelengths of the multiwavelength Raman pump laser, it is possible to multiplex a great number of sensors, but also, reusing the wavelengths.

There is a small difference between the configurations of Fig. 1(a) and Fig. 1(b). In the latter, the signal laser do not enter the first 90% coupler before being detected, so that we do not loose 10 dB in passing from the coupler to the detector. Moreover, the system is more homogeneous in the outputs of the two sections.

Now, we are going to analyze the pump power necessary to obtain transparency (constant optical power throughout the whole optical path) at the end of the second section. The input signal power that enters the first circulator is of –11.5 dBm, so that the power obtained at the end of the overall bus must be the same, in order to have the transparency condition. Thus, the pump power necessary to have those conditions is 1.1 W. As was shown in Refs. [11-12], it is very important to know the Raman gain profile corresponding to this pump power, in order to locate the FBGs.

In Fig. 2(a) and Fig. 2(b) there are shown the Raman gain profiles from the sensors' position S4 and S8.

The strategy used to locate the FBGs used in Fig. 1(b) is the same followed for the configuration of Fig. 1(a): The FBGs with wavelengths that correspond to low Raman gains in the Raman gain profiles of Fig. 2 must be placed closest to the pump, because that is where the signals experience enough amplification. Conversely, gratings with relatively high Raman gains wavelengths must be located further from the head end. However, the sensors' positions are only valid theoretically, because there are many factors, such as errors in measuring the Raman gain profile, irregular behavior of the FBGs or connectors, which may affect to the gratings' positions. The sensors' positions, as well as their output powers are represented in Table 1.

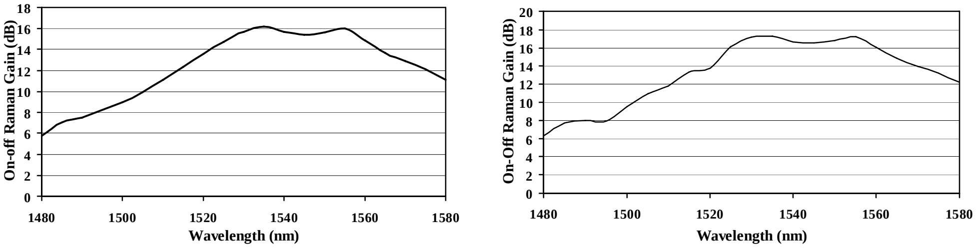

Fig. 2. (a) Measured Raman gain profile for the first section until sensor S4 using 1.1 W pump power. (b) Measured Raman gain profile for the second section until sensor S8 using 1.1 W pump power.

	SECTION 1				SECTION 2			
	S1	S2	S3	S4	S5	S6	S7	S8
λ (nm)	1530.8	1539.7	1536.8	1533.8	1530.8	1539.7	1536.8	1533.8
Power (dBm)	-15.2	-16.24	-15.8	-13.51	-30.84	-33.13	-38.08	-35.08

Table 1. Correct Sensors' Position and Sensors' Output Powers

In Fig. 3(a) and Fig. 3(b) it is represented the FBGs' response in the output of the first and the second section, respectively, using a pump power of 1.1 W.

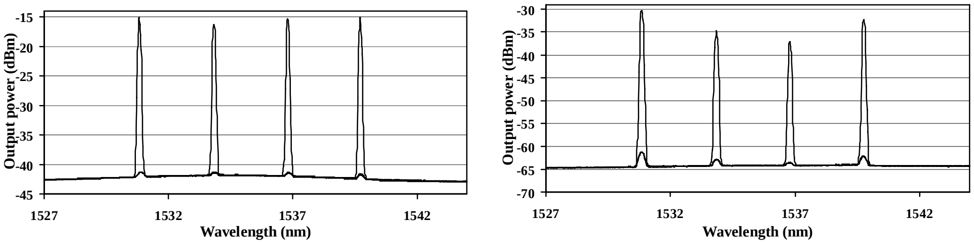

Fig. 3. (a) Amplified output power obtained in the first section with an applied pump power of 1.1 W. (b) Amplified output power obtained in the second section with an applied pump power of 1.1 W.

From Fig. 3(a) we can see that the FBGs are equalized and the average optical signal to noise ratio obtained is 27 dB. From Fig. 3(b), although the FBGs can not be equalized, the average optical signal to noise ratio is maintained closed to 31.5 dB.

The main problem of the second section is that it does not arrived enough pump power, so as to have sufficient Raman gain, and then enable the equalization of the FBGs' response.

However, although there is not enough power, it is possible to obtain the transparency condition at the final end of the bus. The reason is that the gain obtained in the first section is

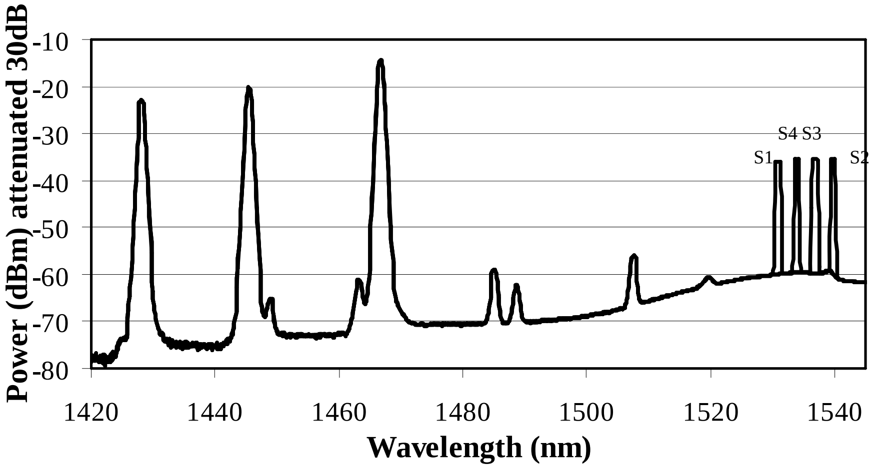

Fig. 4. Output signals coming from the first section to the second.

sufficient to overcome the second section losses, and also to obtain transparency at the end of the overall bus.

To justify all these results, in Fig. 4 there are shown the optical signals that go from the first section to the second one. In this way, we could see the pump level achieved at the second section input. To obtain this figure, the optical power was attenuated 30 dB, in order to avoid damage to the optical spectrum analyzer.

From Fig. 4, the maximum pump level is 15 dBm (pump signals attenuated 30 dB). This is equivalent to 31.6 mW, which is a very low pump power considering a Raman pump network. On the other hand, the FBGs' signals level at the second section input is of -5 dBm, which is higher than the first section input power. It is obtained less amplification in the second section, but with the same FBGs' wavelengths. So, the number of FBGs are reduced to the half.

Thus, it is obtained some degree of equalization in the second section by relocating the FBGs wavelengths. Moreover, the signal power of -5 dBm at the second bus section allows obtaining the transparency power of -11.5 dBm at the end of the overall bus.

3. Conclusions

We have demonstrated a novel distributed Raman amplifying bus network for wavelength division multiplexing of sensors using a multiwavelength Raman pump laser and eight Fiber Bragg Gratings, which has been validated by one previously reported experimental result. By relocating the first four FBGs after distributed amplification in the transmission fiber, we reduced to the half the number of wavelengths needed for addressing the sensors. Using the proposed sensing scheme, we achieved power transparency at a location of approximately 35 km by means of 1.1 W Raman pump power. Our results obtained with high power pumping indicate that there is potential to extend the bus network to serve greater numbers of sensors.

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