Double Raman Amplified Bus Networks for Wavelength-Division Multiplexing of Fiber-Optic Sensors

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***Abstract*—In this paper, three different double Raman fiber bus networks are compared and demonstrated experimentally for the first time as a means of gathering information from wavelength-division-multiplexed optical sensors: the double-bus scheme, the improved double-bus configuration, and the hybrid topology. We report how these structures reduce the received amplified-spontaneous-scattering noise generated. This low-noise configuration yields signal-to-noise ratios over 43 dB and increases the number of sensors that could be multiplexed in a single structure. Furthermore, the last one enables the reutilization of the gratings' wavelengths.**

***Index Terms*—Data buses, distributed amplification, optical-fiber sensors, Raman scattering, wavelength-division multiplexing (WDM).**

I. Introduction

BUS architectures are some of the most widely used multiplexing topologies for sensors, mainly due to their simple cabling requirements. The use in these buses of wavelength-division multiplexing (WDM) is particularly appealing if fiber Bragg gratings (FBGs) are utilized [1].

Nevertheless, fiber bus networks suffer from the disadvantage that the optical power is reduced along the bus, and it limits the number of sensors that can be addressed at acceptable signal-to-noise ratios (SNRs). One approach to overcome this restriction is to locate optical amplifiers [such as erbium-doped fiber amplifiers (EDFAs)] within the bus, but they are costly devices that require electrical power supplies. Alternatively, one can fabricate the bus entirely from erbium-doped fiber with a low doping density to provide distributed gain, but it requires special (and potentially expensive) fiber [2]–[5] and limits the working bandwidth.

The use of Raman amplification in the spine section of the bus to maintain the received powers from the sensors within acceptable bounds has recently been reported [6]–[8]. Moreover, dual-wavelength pumped Raman amplification, together with an EDFA, has been applied in a long-distance sensing system using a FBG [9], [10]. One of the major concerns in the application of Raman amplification is that of laser-safety issues arising out of high launched pump power. In spite of this inconvenience, there is a growing increment in Raman usage in telecommunications domain due to its future applications. Raman amplification upgrades telecommunication networks without replacing the existing fiber. Another possible application is the hybrid combination of data and sensors in a standard telecommunications fiber setup. These advantages make the use of Raman amplifiers more attractive. Despite its price, there is no need to use doped fiber with Raman amplifiers. Thus, there are no constraints to use concrete amplification wavelengths.

In this paper, we demonstrate experimentally three dual-bus structures using Raman amplification. All of them improve the SNRs of the single-bus configuration by reducing the amplified-spontaneous-scattering (ASS) noise detected at the output of the system. The last one shows a method to save wavelengths in these kind of double-bus networks.

II. Experimental Setup

The first structure that we investigate is the dual bus shown in Fig. 1. The upper part of the structure was previously reported in [6]. It is a single-fiber bus that consists of a standard single-mode fiber (ITU-G.652 compliant) spine section that connects a series array of directional couplers leading to sensing elements, followed by the gratings. The reflected signals coming from the sensors can be collected at the head of the bus, if an additional coupler is introduced after the first coupler [6].

In the alternative dual-bus structure of Fig. 1, there is a lower fiber collecting bus, which enables the signals to be detected at the same or at a different remote location where necessary. Our results show that the dual-bus network offers additional benefits over single-bus structures in terms of SNR when Raman amplification is used.

This setup was used for WDM four photonic sensors that induced optical intensity modulation in response to temperature variations [11], although any kind of amplitude-modulation photonic sensor could have been used. In fact, the amplitude sensors have been removed from the original scheme in order to make the power measurements independent of the particular sensors used and to make the results more general.

The number of signals launched on to the spine is equal to the number of sensors, and they all lie within the Raman gain profile. All the wavelengths are tapped off at every directional

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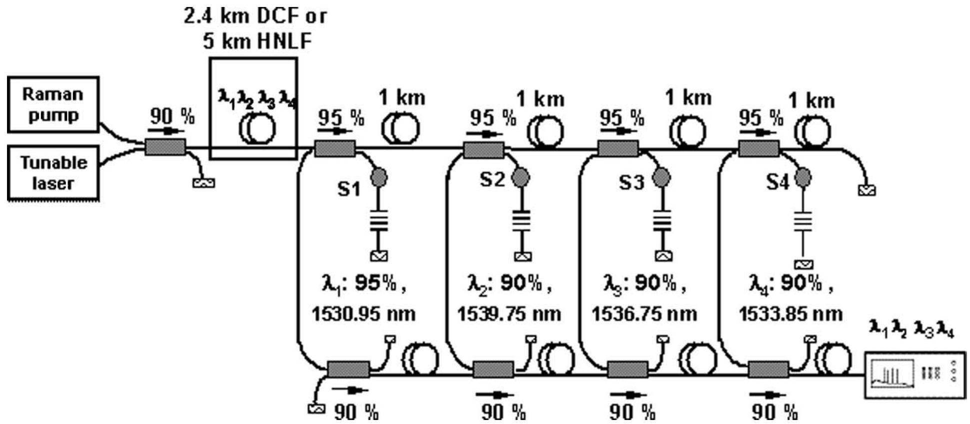

Fig. 1. WDM optical-fiber dual-bus network with distributed gain for sensors including a nonamplifying lower bus. DCF: Dispersion-compensating fiber; HNLF: Highly nonlinear fiber; S1–S4: Location of sensors. The fiber lengths and the grating peak wavelengths and reflectivities are indicated.

coupler and guided by standard single-mode fiber to a sensor. The grating located after the sensor reflects only the signal of predetermined wavelength, which uniquely identifies the sensor. After crossing the sensor again, the reflected light is returned to both spines of the double bus and then to the detectors placed at the end of the lower bus or, simultaneously, at the head of the upper bus if a resilient bus structure is desired.

The signal was provided by a tunable laser source (1460–1580 nm) with an output power of -10 dBm and a spectral linewidth of 5 MHz. The pump laser is a multiorder fiber Raman laser that radiates in three lines: 1428, 1445, and 1466 nm. It could deliver up to 3.2-W power into the fiber prior to the launch coupler. The launch 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 gain values.

In all the sensor networks proposed, the Raman pumps and the signal are combined with a 10 : 90 coupler. Although this introduced a more than 10-dB loss to the signal compared to a signal-pump WDM, we obtained some benefits such as the suppression of lasing (instability) problems that might happen if WDM couplers were used in an amplified network like this. Also, we could design structures used in telecommunications to make data and sensors hybrid networks and, finally, the utilization of directional couplers in the spine of the bus instead of WDM allows the sensor's change of position or replacement (different wavelength) without touching the spine of the bus [12]. Moreover, we wanted to make the most economic configurations and WDMs are more expensive than couplers. That is why there was also used in the lower bus branch a 10 : 90 coupler instead of a WDM.

The peak wavelengths and reflectivities of the gratings are marked on Fig. 1. They had a wavelength variation with temperature of 0.01 nm/°C. The gratings were situated in the networks according to the Raman gain profile corresponding at each pump power.

Two different preamplifying schemes were studied for the dual-bus network depending on the fiber added after the Raman pump laser: The topology with 2.4 km of dispersion-compensating fiber (DCF) and the configuration with 5 km of highly nonlinear fiber (HNLF) as preamplifiers.

DCF shows relatively high Raman amplification; however, the low power conversion efficiency is considered to be a major difficulty that must be overcome [13]. In order to enhance the gain of the Raman amplifier, we have proposed HNLF with a Raman gain coefficient of 2.2 $W^{-1}km^{-1}$ and attenuation lower than 0.4 dB/km around 1550 nm. Moreover, DCF has a raised germania content and, therefore, a somewhat higher loss coefficient than SMF. We have measured a fiber loss of 0.55 dB/km for the DCF. The availability of new high-power optical sources in the 1550-nm wavelength range as well as the development of HNLFs offer increased possibilities to design devices relying on nonlinear effects in optical fibers [14].

By adding the DCF or the HNLF, there is enough global 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.

It is very important to know the Raman gain profile corresponding to each pump power in order to locate the FBGs. This is possible as a result of the positioning of the wavelengths. Thus, the strategy used for the double bus to locate the FBGs was to place the gratings corresponding to low Raman gains in the Raman gain profile closest to the pump because it is where the signals experience enough interaction lengths to amplify. Conversely, gratings with relatively high Raman gain wavelengths were located further from the head end.

In Fig. 2 is represented the Raman gain profile measured for the configuration of Fig. 1 using DCF with a pump power of 1.3 W. Recently, all-Raman systems have been demonstrated using a combination of Raman amplification in the transmission fiber and dispersion-compensating Raman amplifiers [15], [16].

The original double-bus topology has been modified to reduce the ASS noise generated by the fiber. The improved double-fiber bus is that of Fig. 2. S1, . . . , S4 show the positions the sensors ought to take in the new network, although these sensors have been removed in the interest of generalization, as already mentioned. The upper and lower bus structures are identical to those on the original setup, but the connections between both buses and the position of the sensors and FBGs have been modified. As in the previous case, this is a resilient bus structure and the configurations using 2.4 km of DCF and 5 km of HNLF were analyzed.

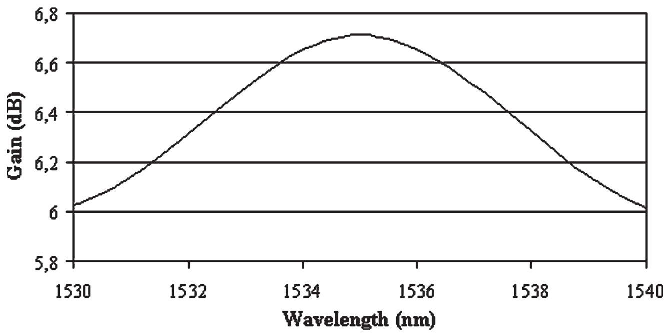

Fig. 2. Measured Raman gain profile for the original configuration using DCF with a pump power of 1.3 W.

In the case of using 2.4 km of DCF, the location of sensors S3 and S4 of Fig. 3 would be interchanged, according to the Raman gain profile. Thus, S1, S2, S3, and S4 would correspond to 1530.95, 1539.75, 1536.75, and 1533.85 nm, respectively.

Finally, we propose a hybrid amplifier composed of two double-bus networks for WDM of eight FBGs and an EDFA as shown in Fig. 4. This topology reduces the number of addressing wavelengths needed at the head of the system. Furthermore, by relocating the FBGs' wavelengths of a first double bus, it obtained the power transparency at the end of the overall configuration. We show how the topology allows the received powers from the first double-bus sensors to be equalized and partially amplify the overall network. We investigate how the performance depends on the launched pump power. The peak wavelengths and reflectivities of the gratings are marked on Fig. 4.

The main objective of the network shown in Fig. 4 was WDM of eight sensors saving addressing wavelengths. Thus, we used pairs of FBGs with the same wavelength in order to save the half of wavelengths and, therefore, reducing the wavelengths' source complexity.

There are two double-bus networks; therefore, it is possible to relocate the first four dual-bus wavelengths into the other. There are two outputs to measure the received signals at those points (marked in Fig. 4 as Output Dual Bus 1 and Output Dual Bus 2) by means of an optical spectrum analyzer. The two dual-bus topologies follow the same configuration and used the same four FBGs. Therefore, the four signal wavelengths of the head of the network are reutilized, reducing the complexity of the laser source required. An additional advantage is that the wavelengths could be relocated to provide power equalization.

III. Experimental Results of Double-Bus Networks

A. Double Bus and Improved Double Bus

In order to evaluate an amplifying network, we define a bus spine transparency power. This is the value of the Raman pump power that is sufficient to overcome the signal attenuation due to the fiber and discrete losses experienced at the couplers in passing from one amplifying span to the next.

To increase the values of SNR that are obtained with the single structure, we propose the use of the double-bus topology presented in Fig. 1, in which the upper bus is built with couplers with a 5% coupling ratio, and the lower one is formed by couplers with a 10% coupling ratio. In this case, the return signal from the sensors is collected in the lower bus.

In the dual-bus structure, the bus spine transparency power was 1.2 W in the case of using HNLF in the preamplifier stage and 1.3 W if DCF was used as preamplifier.

In the double configuration, the ASS noise level coming from the single-mode fiber is highly attenuated when it passes through the 95 : 5 and the 90 : 10 couplers. The reduction of the ASS level translates into an increment of approximately 20 dB in the SNR values compared to the single bus of [6], which turn out to be greater than 37 dB for the DCF and higher than 38 dB when HNLF was used.

The power difference between channels has a maximum value of 2 dB for the DCF and of 1 dB for the HNLF.

The original experimental double-bus configuration has been modified to completely remove the ASS noise generated by the fiber. In the improved double-fiber bus configuration, the pump power using nonlinear fiber (HNLF) was 400 mW, whereas with the DCF, it was 450 mW. The results obtained for both the original and the improved double-bus using DCF and HNLF fibers are presented in Figs. 5 and 6.

The expected noise-level reduction provided by the improved structure has been tested on the four channels, with the tunable laser set to each wavelength. The same allocation technique used in double-bus configuration should be applied in this new structure to reduce power differences between channels. A comparison of SNR values obtained for both double-bus topologies using HNLF is presented in Table I. These were calculated using the acquisition software of the Optical Spectrum Analyzer HP70951B. The procedure that followed consisted in measuring the signal and ASS noise powers at each of the four grating wavelengths. We assumed some filtering in reception.

In both double-bus configurations, the SNRs achieved were increased with respect to the values yielded by the single-bus topology. However, SNR values above 42 dB were obtained for the improved double-bus topology when HNLF was used and with a lower pump power.

SNR is mainly taken advantage of in the accurate sensing of the fiber-optic sensors. As stated before, the networks proposed are for all type of transmittive sensors [17] or for sensors based on FBGs.

We show the optical spectrum obtained at the output of the Raman amplifier using 1 m of single-mode fiber and at the output of the improved double-bus network using HNLF in Figs. 7 and 8, respectively. Graphs and SNRs obtained for the case of using DCF are not included so that this paper will be less complicated.

The Raman pump power was attenuated to 30 dB before entering the optical spectrum analyzer in order not to damage it.

A comparison of SNR values obtained for the three pump wavelengths at the output of the Raman amplifier and at the output of the improved double-bus topology using HNLF is performed in Table II.

As shown in Table II, the pump signal has been highly attenuated after traversing the entire bus network to provide amplification to the signal laser.

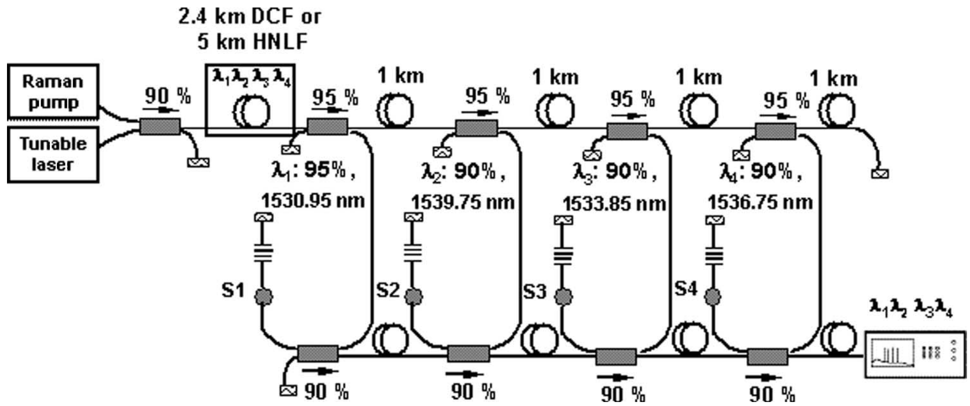

Fig. 3. Improved double-bus topology for WDM of optical sensors. DCF: Dispersion-compensating fiber; HNLF: Highly nonlinear fiber; S1–S4: Location of sensors. The fiber lengths and the grating peak wavelengths and reflectivities are indicated.

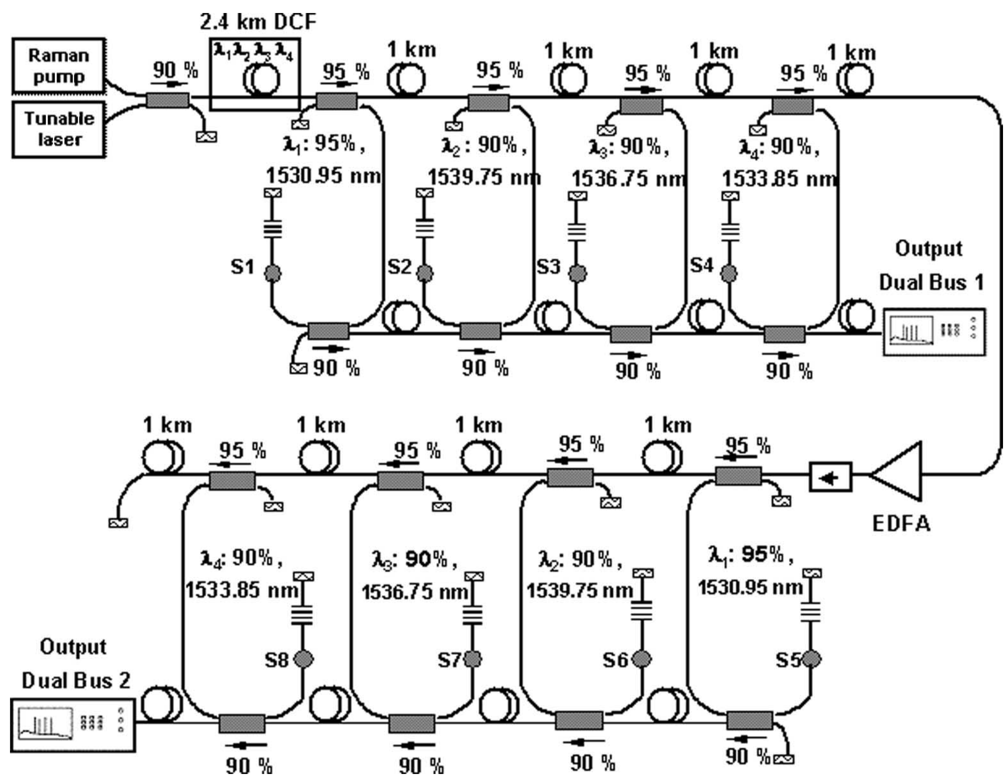

Fig. 4. Experimental setup for a hybrid amplifier. EDFA: Erbium-doped fiber amplifier; DCF: Dispersion compensating fiber.

We show in Fig. 9 the ASS dependence with the Raman pump power. As shown in Fig. 9, the ASS noise increases with the pump power.

B. Reutilization of Multiplexing Wavelengths

The schematic diagram of the proposed hybrid distributed Raman fiber amplifier is shown in Fig. 4. In the first double-bus network, after the initial 90% coupler, we included a span of 2.4 km of DCF. We applied the same allocation technique that we used in both double-bus configurations to reduce power differences between channels.

In this configuration, there were used two double-bus networks formed by couplers of 5% and 10% coupling ratio.

This setup was used for WDM of eight FBGs.

It was made a first attempt to use Raman amplification for both dual-bus topologies. Thus, a 50% coupler on the header was used to divide the Raman pump power. The problem with this configuration was that the pump power was not sufficient to obtain the transparency condition along the two double-bus configurations.

In order to achieve the transparency condition, it was analyzed that the hybrid topology based on the use of both Raman and EDFA amplification, as shown in Fig. 4. Here, the amplification stage of one of the double-bus networks was comprised of the Raman pump amplifier and 2.4 km of DCF, as already mentioned. The Raman pump power was 1.99 W for this configuration. As for the other double-bus scheme, an EDFA was used with a low pump power of 12.2 dBm that gives the extra amplification required.

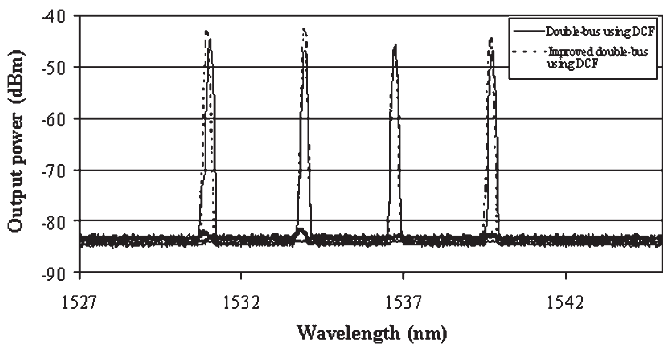

Fig. 5. Amplified output power obtained for the double-bus configuration using DCF with a pump power of 1.3 W and for the improved double-bus configuration using DCF with a pump power of 450 mW.

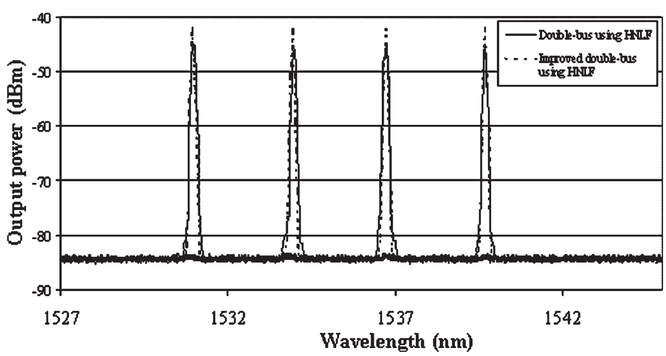

Fig. 6. Amplified output power obtained for the double-bus configuration using HNLF with a pump power of 1.2 W and for the improved double-bus configuration using HNLF with a pump power of 400 mW.

TABLE I
SIGNAL POWER, NOISE LEVEL, AND SNR FOR BOTH DOUBLE-BUS TOPOLOGIES USING HNLF

	Double-bus			Improved double-bus		
Wavelength, nm	Signal (dBm)	Noise (dBm)	SNR (dB)	Signal (dBm)	Noise (dBm)	SNR (dB)
1530.95	-45.0	-83.3	38.3	-42.2	-84.3	42.1
1533.85	-46.0	-84.0	38.0	-42.3	-84.5	42.2
1536.75	-45.3	-83.3	38.0	-42.3	-84.8	42.5
1539.75	-45.0	-83.6	38.6	-42.2	-84.5	42.3

Now, we obtained the transparency condition for the eight sensor structure. As already stated, the wavelength selection will be carried out by means of FBGs. These gratings will also be used for wavelength tuning of the sources and as transducer elements when using the system as a sensor multiplexing scheme.

The output spectrum of the first dual Raman fiber bus amplifier is shown in Fig. 10. The four output channels give optical SNRs around 39 dB. The power of each of the four output channels is around −42.2 dBm, and the maximum peak difference between the four channels is approximately 1 dB.

In Fig. 11, optical signals (right) and Raman pump lines (left) that go from the first part of the dual-bus network to the second one are shown. In this way, we could see the low residual Raman pump levels achieved at the second dual-bus input. Therefore, it is necessary to amplify this signal in order to obtain the transparency condition. On the other hand, the FBGs' signal level at the second dual-bus input is −34.3 dBm.

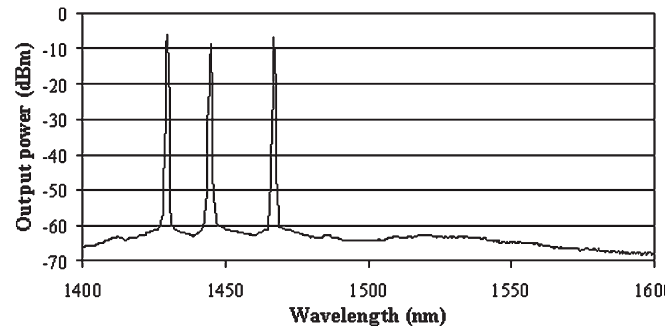

Fig. 7. Optical spectrum at the output of the Raman amplifier attenuated at 30 dB.

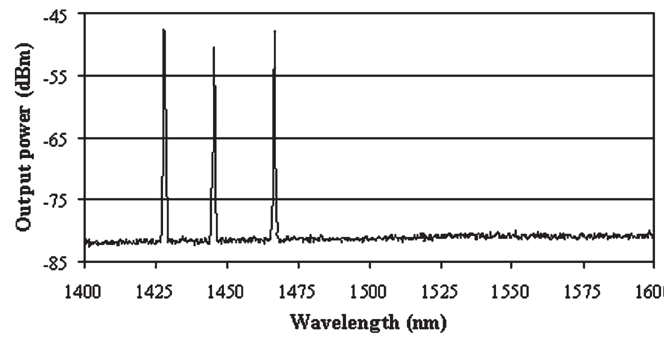

Fig. 8. Optical spectrum at the output of the improved double-bus network using HNLF.

TABLE II
SIGNAL POWER, NOISE LEVEL, AND SNR FOR THE OUTPUTS OF THE RAMAN AMPLIFIER AND FOR THE IMPROVED DOUBLE-BUS TOPOLOGY USING HNLF

	Double-bus			Improved double-bus		
Wavelength, nm	Signal (dBm)	Noise (dBm)	SNR (dB)	Signal (dBm)	Noise (dBm)	SNR (dB)
1428	-6.0	-60.9	54.9	-47.6	-81.8	34.2
1445	-8.6	-61.0	52.4	-50.6	-81.6	31.0
1466	-7.0	-61.0	54.0	-47.9	-81.6	33.7

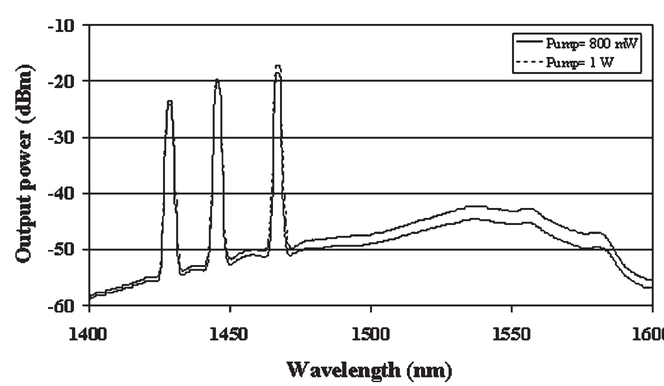

Fig. 9. ASS dependence with the Raman pump power level.

The amplitude equalization in the second section is achieved by relocating the FBGs' wavelengths.

With this structure, the required number of signal wavelengths for the network are reduced to half. The price to pay is the need of an extra fiber to collect the signals coming from the first section of the structure, but using this combination of Raman and EDFA amplification, we obtain an improvement in the SNR values [18], which are now around 43.2 dB. We also

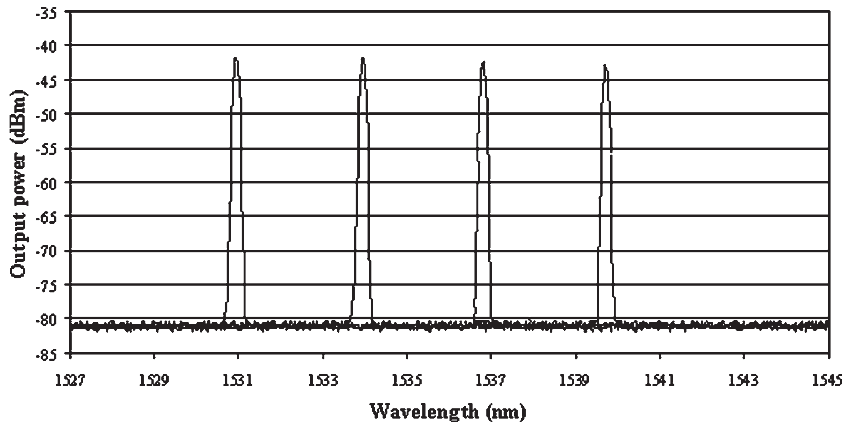

Fig. 10. Measured output spectrum of the first part of the dual-bus network.

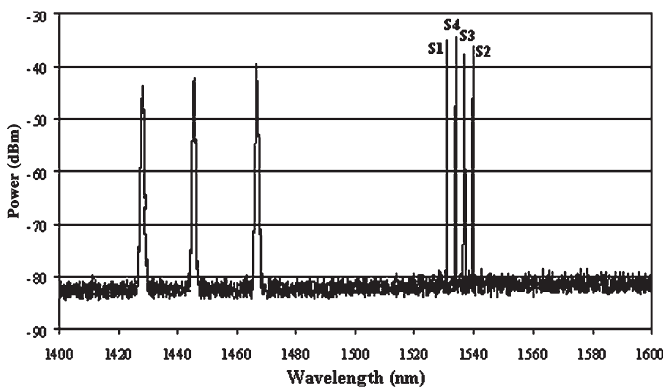

Fig. 11. Output signals coming from the first dual-bus to the second.

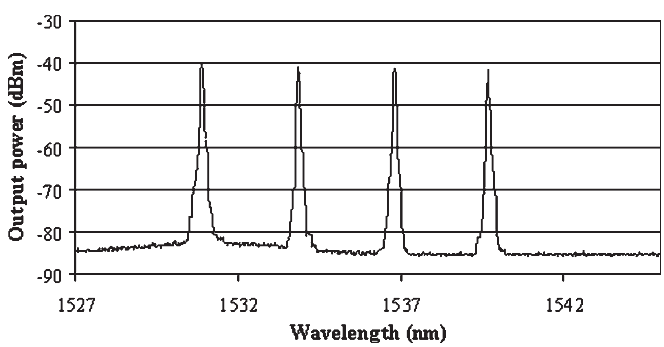

Fig. 12. Measured output spectrum of the second part of the dual-bus network.

obtain the transparency condition at the end of the overall configuration. Fig. 12 shows the obtained detected output signals corresponding to the second part of this dual-bus configuration.

From Fig. 10, we can see that the FBGs are equalized and that the average optical SNR obtained is 39 dB for the first four FBGs. In Fig. 12, the average optical SNR for the last four FBGs is maintained close to 43.4 dB.

IV. Conclusion

We have compared experimentally, for the first time, three different distributed Raman amplifying dual-bus networks for WDM of sensors. We have shown the advantage in terms of signal-to-noise values of the double-distributed optical amplifier fiber bus network versus the single-bus topology. By simultaneously extracting the signals at the head of the upper bus and at the end of the lower bus, these structures present an inherent resilient capacity that makes them particularly appealing. The ASS noise generated by the fiber can be virtually eliminated by using the proposed improved double-bus configuration. This structure yields SNR values over 42 dB when HNLF was used. The reduction of the amplification noise will allow a higher number of sensors to be multiplexed together without degrading the SNRs achieved. All this can be accomplished without increasing the complexity of double-bus architectures and without introducing any new noise sources. Finally, we have also experimentally demonstrated a third configuration. It was a hybrid amplified network using two cascaded amplified bus networks, including Raman and EDFA amplification for WDM of eight FBGs. By relocating the first four FBGs after distributed amplification in the transmission fiber, we reduced to half the number of wavelengths needed for addressing the sensors. Using the proposed hybrid configuration, SNR values over 43 dB have been, obtained, and we achieved power transparency along the overall network.

References

[1] A. Dandridge and C. Kirkendell, “Passive fiber optic sensor networks,” in *Handbook of Optical Fiber Sensing Technology*, J. M. López-Higuera, Ed. Hoboken, NJ: Wiley, 2002, ch. 21.

[2] M. López-Amo, L. T. Blair, and P. Urquhart, “Wavelength-division-multiplexed distributed optical fiber amplifier bus network for data and sensors,” *Opt. Lett.*, vol. 18, no. 14, pp. 1159–1161, Jul. 1993.

[3] 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. Lightw. Technol.*, vol. 16, no. 4, pp. 485–489, Apr. 1998.

[4] S. Abad, M. Lopez-Amo, J. Lopez-Higuera, D. Benito, A. Unanua, and E. Achaerandio, “Single and double distributed optical amplifier fiber bus networks with wavelength division multiplexing for photonic sensors,” *Opt. Lett.*, vol. 24, no. 12, pp. 805–807, Jun. 1999.

[5] V. Montoya, M. López-Amo, and S. Abad, “Improved double-fiber-bus with distributed optical amplification for wavelength-division multiplexing of photonic sensors,” *IEEE Photon. Technol. Lett.*, vol. 12, no. 9, pp. 1270–1272, Sep. 2000.

[6] 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. OFS*, Bruges, Belgium, 2005, vol. 5855, pp. 242–244.

[7] S. Diaz, G. Lasheras, and M. Lopez-Amo, “WDM bi-directional transmission over 35 km amplified fiber-optic bus network using Raman

amplification for optical sensors," *Opt. Express*, vol. 13, no. 24, pp. 9666–9671, Nov. 2005.
[8] S. Diaz and M. Lopez-Amo, "Comparison of wavelength-division-multiplexed distributed fiber Raman amplifier networks for sensors," *Opt. Express*, vol. 14, no. 4, pp. 1401–1407, Jan. 2006.
[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,* vol. 12, no. 15, pp. 3515–3520, Jul. 2004.
[10] Y. Nakajima, Y. Sindo, and T. Yoshikawa, "Novel concept as long-distance transmission FBG sensor system using distributed Raman amplifier," in *Proc. 16th Int. Conf. OFS*, Nara, Japan, 2003, pp. 530–533.
[11] P. Datta, I. Matías, C. Aramburu, A. Bakas, M. López-Amo, and J. M. Otón, "Tapered optical fiber temperature sensor," *Microw. Opt. Technol. Lett.*, vol. 11, no. 2, pp. 93–95, Feb. 1996.
[12] M. Lopez-Amo and S. Abad, "Amplified fiber-optic networks for sensor multiplexing," *Jpn. J. Appl. Phys.*, vol. 45, no. 8B, pp. 6626–6631, 2006.
[13] T. Amano, K. Okamoto, T. Tsuzaki, M. Kabui, and M. Shigematsu, "Hybrid dispersion compensating Raman amplifier module employing highly nonlinear fiber," in *Proc. Int. OFC*, Atlanta, GA, 2003, pp. 306–307.
[14] J. Hansryd, F. Dross, M. Westlund, P. A. Andrekson, and S. N. Knudsen, "Increase of the SBS threshold in a short highly nonlinear fiber by applying a temperature distribution," *J. Lightw. Technol.*, vol. 19, no. 11, pp. 1691–1697, Nov. 2001.
[15] A. H. Gnauck, G. Raybon, S. Chandrasekhar, J. Leuthold *et al.,* "2.5 Tb/s (64 × 42.7 Gb/s) transmission over 40 × 100 km NZDSF using RZ-DPSK format and all-Raman-amplified spans," in *Proc. OFC,* Anaheim, CA, 2002, pp. FC2-1–FC2-3.
[16] B. Zhu, L. Leng, L. E. Nelson *et al.*, "3.2 Tb/s (80 × 42.7 Gb/s) transmission over 20 × 100 km of non-zero dispersion fibre with simultaneous C+ L-band dispersion compensation," in *Proc. OFC*, Anaheim, CA, 2002, pp. FC8-1–FC8-3.
[17] S. T. Vohra, "Optical fiber gratings applications," in *Handbook of Optical Fiber Sensing Technology*, J. M. López-Higuera, Ed. Hoboken, NJ: Wiley, 2002, ch. 23.
[18] H. Masuda, "Hybrid EDFA/Raman amplifiers," in *Raman Amplifiers for Telecommunications 2*, M. N. Islam, Ed. New York: Springer-Verlag, 2004, ch. 13.

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