Resilient Amplified Double Ring Optical Networks to Multiplex Optical Fibre Sensors

<table>
<thead>
<tr>
<th>Journal:</th>
<th>Journal of Lightwave Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manuscript ID:</td>
<td>JLT-11063-2008</td>
</tr>
<tr>
<td>Manuscript Type:</td>
<td>Original Paper</td>
</tr>
<tr>
<td>Date Submitted by the Author:</td>
<td>02-Oct-2008</td>
</tr>
<tr>
<td>Complete List of Authors:</td>
<td>Fernández-Vallejo, Montserrat; Public University of Navarra, Department of Electric and Electronic Engineering Perez-Herrean, Rosa Ana; Public University of Navarra, Department of Electric and Electronic Engineering Elosua, Cesar; Public University of Navarra, Department of Electric and Electronic Engineering Diaz, Silvia; Public University of Navarra, Department of Electric and Electronic Engineering Urquhart, Paul; Public University of Navarra, Department of Electric and Electronic Engineering Barajain, Candido; Public University of Navarra, Department of Electric and Electronic Engineering Lopez-Amo, Manuel; Public University of Navarra, Department of Electric and Electronic Engineering</td>
</tr>
<tr>
<td>Key Words:</td>
<td>Fibre Bragg grating (FBG), Raman lasers, Multiplexing, fibre optics sensors</td>
</tr>
</tbody>
</table>
Resilient Amplified Double Ring Optical Networks to Multiplex Optical Fibre Sensors

Montserrat Fernandez-Vallejo, Rosa Ana Pérez-Herrera, Cesar Eliaoa, Silvia Diaz, Paul Urquhart, Candido Baraiain and Manuel López-Amo Senior Member, IEEE

Abstract— We report the experimental demonstration of two configurations of an amplified optical fibre double ring network for the multiplexing of sensors. The networks are designed to be inherently resilient to fibre failures because they enable simultaneous interrogation of all the optical fibre sensors using both rings. The first design demonstrates the feasibility of the so called “dedicated protection” and the second one “shared protection” for fibre optic intensity sensors. Raman amplification is used to overcome the losses of the couplers used in the rings, providing power transparency. The first network uses Raman amplification in both constituent rings but in the second one Raman pumping is activated only when a fibre failure occurs. We demonstrate how the topology allows the received powers from the sensors to be equalized.

Index Terms— Fibre Bragg grating (FBG), fibre optics sensors, Raman lasers, multiplexing.

I. INTRODUCTION

Arrays of sensors have many applications in environmental, safety and security monitoring and they can be interconnected by wireless, copper wire or optical fibre [1], [2]. Single mode fibre offers the key advantages of almost total immunity to external electromagnetic interference, multi-path reflections from natural and man-made objects and interruptions by bad weather. Moreover, they exhibit vast bandwidths and low transmission losses, enabling very wide geographical coverage. Intrusive data interception is more difficult when using dielectric optical waveguide transmission media than either free-space radio propagation or metallic wires. Where necessary, fibre interconnects allow the sensors to be inserted within the structures being monitored and they reduce the risk of sparking in combustible environments [2].

Despite their marked advantages, optical fibre networks for sensors pose two challenges. The first is the need to increase the number of sensors that can be multiplexed on a single network [2], which is especially important in applications such as acoustic sensors arrays [3] or structural health monitoring and it is usually solved using optical amplification [4]-[6] The second challenge is to ensure service continuity in the event of point failure(s) on the network [7]-[11]. The purpose of this paper is to address these issues.

Telecommunications service providers are well aware of the loss of revenue and customer confidence that follows accidental or malicious damage to transmission infrastructure [12]. To this end, metropolitan and wide area networks are routinely configured as “self-healing rings” to perform “protection switching” in the event of a severed fibre [13], [14]. In contrast, there are relatively few reports of fibre-based networks for sensors that can survive point failures. We believe that the ability to operate despite failures will become increasingly important as the use of optical networking of sensors grows, especially for safety-critical applications.

We report an experimental study of wavelength division multiplexed (WDM) single mode optical fibre networks to provide “resilience”, the ability to survive failures at one or more points. We use double ring topologies to interconnect fibre Bragg gratings (FBGs), which serve two purposes: (a) where necessary, to fulfill the sensing function in their own right and (b) through the judicious choice of reflected wavelengths, to provide unique sensor identification. We also demonstrate a variant of the network, in which the sensing is performed by separate tapered optical fibre-based elements but the FBGs continue to provide unique sensor identification. The tapered optical fibres have previously been reported for the sensing of measurands that can be categorized as chemical [16] (humidity and gas concentration) and physical [17], [18] (temperature, vibrations and displacements). We describe how these sensors can be optimised to provide the highest sensitivity with the lowest loss.

Both configurations of the double ring network include broadband directional couplers to act as taps, which impose loss on the propagating waves and could thereby constrain the number of sensors. However, we incorporate a combination of discrete and distributed Raman amplification [18], [19] to compensate, demonstrating the potential to multiplex larger numbers of sensors.

II. RESILIENT AMPLIFIED DOUBLE RING OPTICAL NETWORKS

Optical networks for sensors differ from their telecommunications counterparts in many ways that determine their design and operation. The sensors are preferably small,
low cost and electrically passive. Fibre interconnects transport unmodulated waves to interrogate the sensors, where the measurand imposes a modulation, before passing to the receivers. Operation is analogue with modulation rates that are some orders of magnitude lower than in communications and thus slow switching speeds can be acceptable. In contrast, communications networks normally convey digital signals between large nodes, where electrical power supplies and optical amplification are available. Protection switching must normally be performed in under 50 ms to limit the data loss. Digital data frames or packets with overhead bytes for synchronisation, error checking, signalling, protection switching and other vital management functions can be included. The synchronisation needed for packet interleaving in time division multiple access can be ensured through digital ranging protocols [20]. However, in the absence of (costly) power feeds outside the end nodes, none of these facilities is available in sensor networks, precluding many of the network protection techniques used in communications. Although one can seek guidance from telecommunications practice, new approaches are required for analogue sensor network resilience.

When a fibre failure occurs the receiver experiences the loss of one or more channels in one of its fibre inputs. The most straightforward response then is to switch the receiver to the other input to resume normal service. Normally, all channels are switched collectively by only one switch in front of the receiver and such operation is known as “line” protection [12], [13], [14]. The combination of dedicated and line protection is a relatively low complexity means of providing resilience. Where necessary, the transmitter and receiver can be co-located in one node, possibly on the same circuit card, eliminating the need for telemetry signalling between them and this greatly simplifies the control software [10]. It also simplifies the electrical power supply requirements.

III. EXPERIMENTAL CONFIGURATIONS

A. First Network Configuration

A simplified version of the previous network has been experimentally developed in order to check the feasibility of the system. The experimental details are shown in Fig. 2, which is a double ring amplified network for 4 FBG sensors. This network uses fibre Bragg gratings (FBGs) for both the sensing function and the unique identification of the sensors, according to the wavelengths reflected. A tuneable laser source (1460-1580 nm) with an output power of 0.2 dBm and a spectral line-width of 5 MHz was used. Pumping was provided by a Raman laser that emitted at 1445 nm and could deliver up to 3.2 W of power into a single mode fibre. Although the launched pump power was polarization scrambled, there was a small residual elliptical polarization of the signal laser. As Fig. 2 shows, we launched the signal and pump waves co-directionally on to the double-ring network. The spine of the rings is formed by couplers of 5% coupling ratio, which are interconnected by 1 km spans of standard single-mode fibre. The 5% output from the couplers entered the FBGs and was reflected back via the couplers on to the
rings.

Each FBG in the network had a reflectivity higher than 90% and a wavelength variation with temperature of 0.01 nm/°C. We used gratings at 1531.03, 1535.33, 1538.35 and 1539.85 nm, each one having a 0.3 nm bandwidth. An additional advantage of this structure is that the wavelengths could be located, as we did, to provide power equalization.

The first amplification stage shown in Fig. 2 consisted of 2.4 km of DCF to provide discrete Raman gain. Thereafter, a 50% coupler directed the residual pump and WDM signals to the transmission fibre in the rings for secondary amplification. We obtained power transparency (constant optical power for the signals throughout the whole path of the rings) for the two rings and we equalized the received powers from the sensors with ± 0.5 dB errors estimated in the gain values. As described in [6] the initial 2.4 km section of DCF provided a degree of equalization of the received powers from the gratings. This is because 2.4 km is sufficient to obtain Raman gain for every grating, even for the one that is spectrally closest to the pump. In this case, the strategy was to place the gratings corresponding to relatively high Raman gain wavelengths furthest from the laser source input, whereas gratings corresponding to low Raman gain wavelengths were located closest to the pump input, because that is where the signals experience sufficient amplification [5], [6].

We used gratings at 1531.03, 1535.33, 1538.35 and 1539.85 nm, each one having a 0.3 nm bandwidth. An additional advantage of this structure is that the wavelengths could be located, as we did, to provide power equalization.

The first amplification stage shown in Fig. 2 consisted of 2.4 km of DCF to provide discrete Raman gain. Thereafter, a 50% coupler directed the residual pump and WDM signals to the transmission fibre in the rings for secondary amplification. We obtained power transparency (constant optical power for the signals throughout the whole path of the rings) for the two rings and we equalized the received powers from the sensors with ± 0.5 dB errors estimated in the gain values. As described in [6] the initial 2.4 km section of DCF provided a degree of equalization of the received powers from the gratings. This is because 2.4 km is sufficient to obtain Raman gain for every grating, even for the one that is spectrally closest to the pump. In this case, the strategy was to place the gratings corresponding to relatively high Raman gain wavelengths furthest from the laser source input, whereas gratings corresponding to low Raman gain wavelengths were located closest to the pump input, because that is where the signals experience sufficient amplification [5], [6].

![Diagram](image-url)

Fig 2. Experimental set-up for the first double ring amplifier. WDM = wavelength division multiplexer, OSA = optical spectrum analyser, DCF = dispersion compensating fibre, SMF = standard single mode fibre, FBG = fibre Bragg grating. ～ index matched fibre end to suppress reflections.

The received signals (marked in Fig. 1 as Detector Units) were measured by means of an optical spectrum analyser (OSA). The transparency condition applied when 600 mW and 400 mW of average pump power were launched on to the inner and outer ring, respectively. Figure 3 is a plot of the powers of the four received channels when there is no launched Raman pump power, showing the propagations by both the inner and outer rings. As their losses are almost identical, these responses are almost equal. The four output channels have peaks of around -24.9 dBm, with a variation of ± 0.25 dB and optical signal-to-noise ratio (OSNR) of around 50 dB. The output spectrum of the both rings with Raman amplification at a global pump power of 1.2W power is shown in Fig. 4. The four output channels have peaks of around – 13 dBm, with a variation of ± 0.5 dB and OSNRs of around 48.5 dB. The similarity of the peak powers in this figure for both rings indicates the viability of the dedicated line protection scheme that we propose for the network.

![Diagram](image-url)

Fig 3. Measured output spectra of the two rings without Raman amplification.

![Diagram](image-url)

Fig 4. Measured output spectra of the two rings with a Raman pump power of 1.2 W

B. Tapered Fibre Sensors

The network’s versatility is increased if it can include a broad range of sensors to respond to different measurands. In this section we describe a low-cost optical intensity sensor that has been used to measure temperature [15] and other parameters [15]. It is called the “tapered fibre sensor” and is shown in Fig. 5. A single mode fibre that has been tapered to a narrow waist is fixed on to a substrate at its two ends, forming a bend that lifts off the substrate. The substrate elongates with increasing temperature and contracts with reducing temperature. Such changes affect the curvature of the fibre’s tapered region and thus its transmission loss. Once a calibration has been performed, optical throughput loss can be related to the environmental temperature.

![Diagram](image-url)
The taper in the fibre can be reproducibly fabricated with the aid of a fusion splicer. A normal fusion routine is used, but the splicer’s program is adjusted so that 500 ms after two cleaved-ends have been fused, one of them is pulled a few hundred micrometers. (Other ways for stretching optical fibres are described elsewhere [15, [21].) Once the taper is fixed onto a substrate, an increment in temperature is needed in order to dilate the substrate, increasing the curvature of the taper, and hence, the losses induced by it.

The temperature response of the fibre taper sensors used in the second network configuration was calibrated by heating and cooling in the range of 30°C to 60°C, using a climatic chamber. Our results are shown in Fig 6, which indicates a sensitivity of 0.6dB/°C. The red curve denotes the linear approximation when the temperature increases, and the blue one shows the response to a cooling process. The hysteresis, defined as the difference between the two curves at a given temperature, was never more than 0.12 dB.

C. Second Network Configuration

Our second experimental configuration is designed to enable other types of sensor, such as that described in Section III B, to be included in the network. The design, illustrated in Fig. 7, differs from that in Fig. 2 by the way that we connected the constituent rings. As shown in Fig. 7, four 90:10 inner couplers carry the signal from the rings to the sensors in order to separate the response of both rings. The sensor thus receives most power from the outer ring and the remainder from the inner one. We could thus discriminate which ring had a failure. Due to these different levels of output power in the two rings, the Raman amplification is activated in the system only when a failure is detected in the outer ring. In this case, we will need to increase the power level by means of Raman amplification. Consequently, a switch was used in the experimental set up in order to introduce the interrogating signal in the inner ring in case of failure in the outer ring. A 3 dB coupler was also located in the rings with to extract the signals through the OC by means of an optical spectrum analyser (OSA).

The network in Fig. 7 uses “shared protection” [12], [13], [14] to re-establish service after a failure. In normal operation the interrogating laser is connected to the “working fibres” (the ones forming the outer ring) but when a failure occurs, it is switched to the “protection fibres” (the inner ring). As Fig. 7 shows, there is a 1x2 switch at the head of the network to perform the necessary selection of launch point. Consequently, only the working fibres are used in normal operation and only the protection fibres in the event of a cable failure. Automatic protection switching (APS) protocols are required to control the process and upon completing the switching action, operation is entirely by the protection fibres. As in the network of Fig. 2, telemetry signalling is greatly simplified when the transmitter and receiver are co-located [10].

The configuration shown in Fig. 7 used gratings at 1535.69, 1536.65, 1539.73 and 1545.01 nm, each with a bandwidth of 0.3 nm. The four sensors were as described in Section III B. The signal and pump waves are also launched co-directionally on to the double-ring network and we used the same tuneable signal source as before (Field operation could use either a single wavelength-agile source that systematically scans through the N grating wavelengths, as in [21], or N monochromatic sources). The spine of the rings was formed by couplers of 5% coupling ratio with 1 km connecting spans of standard single-mode fibre. The 5% output from the couplers entered the FBGs and was reflected back via the couplers on to the rings. A wavelength multiplexer allowed the Raman pump to be launched into the inner ring in order to...
obtain amplification. In both rings, the interrogating signal was inserted by means of an optical circulator (OC). This element was also used to recover the output signal and take it to the OSA for measuring.

The output spectra for both rings when the Raman amplifier is off are shown in Fig. 8 (a) and Fig. 8 (b). As revealed, the four output channels have different power levels for the outer ring compared with the inner one. For the outer ring, the four output channels have peaks of around –28.5 dBm, with a variation of ±0.15 dB and OSNRs of around 36.5 dB. For the inner one, the four output channels have peaks of around –46.7 dBm, with a variation of ±0.35 dB and OSNRs of about 20 dB.

When a failure occurs, the state of the switch is changed and the Raman pump power is launched into the inner ring. In that case, the output spectrum of the inner ring when a Raman pump power of 0.8W is inserted is shown in Fig. 9. As a result, the four output channels have peaks of around –28 dBm, with a variation of ±0.8 dB and OSNRs of around 36 dB. There was an OSNR variation of about ±1 dB between the rings due to the different noise level for each one. Once again, the comparison of the spectra in this figure for both rings indicates the capability of the protection scheme that we suggest for the network.

IV. CONCLUSION

We have experimentally demonstrated two novel configurations of WDM optical fibre ring networks for the multiplexing of sensors. Their key attribute is to enable service continuity after a failure in one of their constituent fibres. The first configuration uses fibre Bragg gratings (FBGs) for both the sensing function and the unique identification of the sensors, according to the wavelengths reflected. The second configuration uses separate sensors based on fused optical fibres but the FBGs continue to allow their unique identification. Resilience is provided by dedicated line and shared line protection in the first and second network designs, respectively. The first design is relatively simple to implement and the second one can operate with many sensor types for various measurands. We have used a combination of discrete and distributed Raman amplification to compensate for the losses imposed by the optical taps in the networks, achieving power transparency with total pump powers of 1.2 W and 0.8 W for the first and second ring designs, respectively. Our results therefore indicate the scalability of the networks to serve greater numbers of sensors.

References


Biographies

Montserrat Fernández Vallejo was born in Navarra, Spain, in February 1983. She received the telecommunications engineer degree from the Public University of Navarra, Spain in 2008. She is currently working toward the Ph.D. degree in the “Communications” Doctoral program. Her research interests are in Raman amplifiers, erbium-doped amplifiers, fiber-optic sensors and multiplexing architectures.

Rosa Ana Perez-Herrera was born in Cantabria, Spain, in February 1979. She received the telecommunications engineering degree from the University of Cantabria, Spain in 2004. In 2005 she obtained a scholarship from the Spanish Ministry of Science and Technology and she joined the Optical Communications Group at the Department of Electrical and Electronic Engineering of the Public University of Navarre (Pamplona, Spain). She is currently working toward the Ph.D. degree in the “Communications” Doctoral program. Her research interests are in Raman amplifiers, erbium-doped amplifiers, fiber-optic sensors and multiplexing architectures.

Cesar Elosua received his MS degree in electrical and electronic engineering from the Public University of Navarra (UPNA, Pamplona, Spain) in 2004. In the same year, he obtained a scholarship from the Science and Technology Spanish Ministry and he joined the optical fiber sensor group at the Department of Electrical and Electronic Engineering of the UPNA. During 2008, he has been a visiting Ph.D. student at Limerick University and City University of London. His research interests include fiber optic sensors and network configurations and artificial neural networks signal analysis.

Silvia Diaz was born in Valencia, Spain. She received the Ingeniero de Telecomunicacion degree in 2002. and her Ph.D. degree in 2007. In October 2003, she was a visiting Ph.D. student at the Photonics Group in Universidad de Cantabria, Spain, working on signal processing with distributed fiber optic networks. In November 2004, she became an Assistant Professor in the Electrical and Electronic Engineering department of the Universidad Pública de Navarra. During the summer of 2006, she was a visiting Ph.D. student at the NAM Laboratory at the École Polytechnique Fédérale de Lausanne, Switzerland, working on Brillouin Scattering. Her research interests include distributed non linear amplified networks for optical fiber sensors, Raman amplifiers, erbium-doped amplifiers and their applications in wavelength-division-multiplexing communication systems and networks.

Cándido Baraián received his MS degree in telecommunication from the Polytechnic University of Madrid (UPM, Madrid Spain) in 1990. He received his PhD degree in communications from the Public University of Navarra (UPNA, Pamplona, Spain) in 2002. He is currently the Professor in the Department of Electrical and Electronic Engineering at the Public University of Navarra. His research interests include fiber optic sensors and optical networks.

Manuel Lopez-Amo (M’91, SM ’98) was born in Madrid, Spain, in 1960. He received the telecommunications engineer degree and Ph.D. degrees from the Universidad Politécnica de Madrid, Spain in 1985 and 1989, respectively. From 1985 to 1989, he was a Lecturer in Optical Communications and Electronics at the Photonic Technology Department of the Universidad Politécnica de Madrid. In January 1990, he became an associate professor at the Photonic Technology Department of the Universidad Politécnica de Madrid.
Montserrat Fernández-Vallejo
Department of Electric and Electronic Engineering,
Public University of Navarra,
Edificio de los Tejos,
Pamplona, Spain
Phone:+ 34 948 169055
Fax + 34 948 169720
Email: montserrat.fernandez@unavarra.es

Rosa Ana Perez-Herrera
Department of Electric and Electronic Engineering,
Public University of Navarra,
Edificio de los Tejos,
Pamplona, Spain
Phone:+ 34 948 169055
Fax + 34 948 169720
Email: rosa.perez@unavarra.es

Cesar Elosua
Department of Electric and Electronic Engineering,
Public University of Navarra,
Edificio de los Tejos,
Pamplona, Spain
Phone:+ 34 948 169055
Fax + 34 948 169720
Email: cesar.elosua@unavarra.es

Silvia Diaz
Department of Electric and Electronic Engineering,
Public University of Navarra,
Edificio de los Tejos,
Pamplona, Spain
Phone:+ 34 948 169055
Fax + 34 948 169720
Email: silvia.diaz@unavarra.es

Paul Urquhart
Department of Electric and Electronic Engineering,
Public University of Navarra,
Edificio de los Tejos,
Pamplona, Spain
Phone:+ 34 948 169055
Fax + 34 948 169720
Email: paul.urquhart@unavarra.es

Cándido Bariáin
Department of Electric and Electronic Engineering,
Public University of Navarra,
Edificio de los Tejos,
Pamplona, Spain
Phone:+ 34 948 169055
Fax + 34 948 169720
Email: cba@unavarra.es
Professor Manuel Lopez-Amo
Department of Electric and Electronic Engineering,
Public University of Navarra,
Edificio de los Tejos,
Pamplona, Spain
Phone: +34 948 169055
Fax: +34 948 169720
Email: mla@unavarra.es