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Self-referenced optical networks for remote interrogation of quasi-distributed fiber-optic intensity sensors

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ABSTRACT

Different multiplexing techniques for passively addressing fiber-optic sensors and compensation schemes for overcoming the undesirable optical signal losses to provide self-referenced quasi-distributed sensing from intensity-based fiber-optic point sensors are revisited. Furthermore, a passive wavelength division multiplexing (WDM) network operating in reflective configuration with remote Radio-Frequency self-referenced fiber-optic intensity sensors with electro-optical configuration is proposed. Delay lines in the electrical domain provide more compact sensor-heads and easy-reconfigurable performance of the sensing points. The technique is analyzed following the Z-transform formalism and measurements validating the theoretical model are reported. There are two measurement parameters providing self-referenced remote interrogation for the sensing heads. The paper shows their experimental validation in a 2-sensor network based on tapered SMF micro-displacement sensors, testing sensor self-referencing as well as sensor crosstalk. Those results provide the background to extrapolate them to a quasi-distributed passive CWDM-based 16-sensor network at around 65 km of remote distance from the central office, with possible upgrade to a 25 km-long DWDM-based 48-sensor network.

1. Introduction

The application areas for fiber-optic sensors (FOS) include high-sensitivity military sensor systems, industrial process control sensors, building and home applications, chemical sensing, environmental monitoring and smart structural and material sensing, among others. Those sensors cover a wide variety of physical magnitudes [1]. In each of these areas, the ability to multiplex sensors in a passive optical sensing network can be advantageous by a component costs reduction, ease of electro-optical interfacing and overall system immunity to electromagnetic interference. Moreover, the development of efficient multiplexing techniques enhances the competitiveness of fiber sensors compared with conventional technologies in most application areas in the need to facilitate the efficient interrogation of tens or, perhaps, hundreds of sensors distributed over a complex smart structure. The fiber optic sensor network with large capacity is becoming an inevitable tendency for the sensing industry. Apart from seeing many successful commercial deployments of fiber sensors, novel and function-enhanced fiber sensors have been developed by utilizing specially modified structures and speciality fibers.

In general, current sensing trends put much effort in distributed optical fiber sensors (DOFSs) due to this growth of social and industrial needs for ubiquitous monitoring. These DOFSs, that are based on optical reflectometry technology, can be categorized into two different classes: the truly DOFSs and the quasi-distributed sensing solutions, so-called point fiber sensor arrays, being the latter mostly employing Fiber Bragg Grating (FBG) devices. The former work on the basis of intrinsic scattering of fibers (Raman, Brillouin and Rayleigh) while FBGs-based technology can achieve higher Signal-Noise ratio (SNR) since it possesses much higher back-scattering light coupling efficiency. Although in this last case, the total fiber length is limited by the multiplexing capacity recent advances have even demonstrated high spatial resolution over 6680 FBGs along a 10 m-long fiber [2]. In both cases their capacity for measuring strain or temperature distributions have been widely demonstrated. It must be made clear that both types of sensors may coexist in the same network, resulting in a specific hybrid network type.

One extensively investigated transducing mechanism is the intensity modulation, in which the intensity of the transmitted signal varies in accordance with the measurand. In general, intensity sensors usually are very attractive since they are simple in concept, reliable, small-sized and offer a wide range of applications at lower costs. Although such sensors use a simple but effective measuring process for detection, their main drawback is interference from variation in losses non-correlated to the sensor modulation, so some strategy must be integrated. The implementation of a reference channel may overcome, or at least

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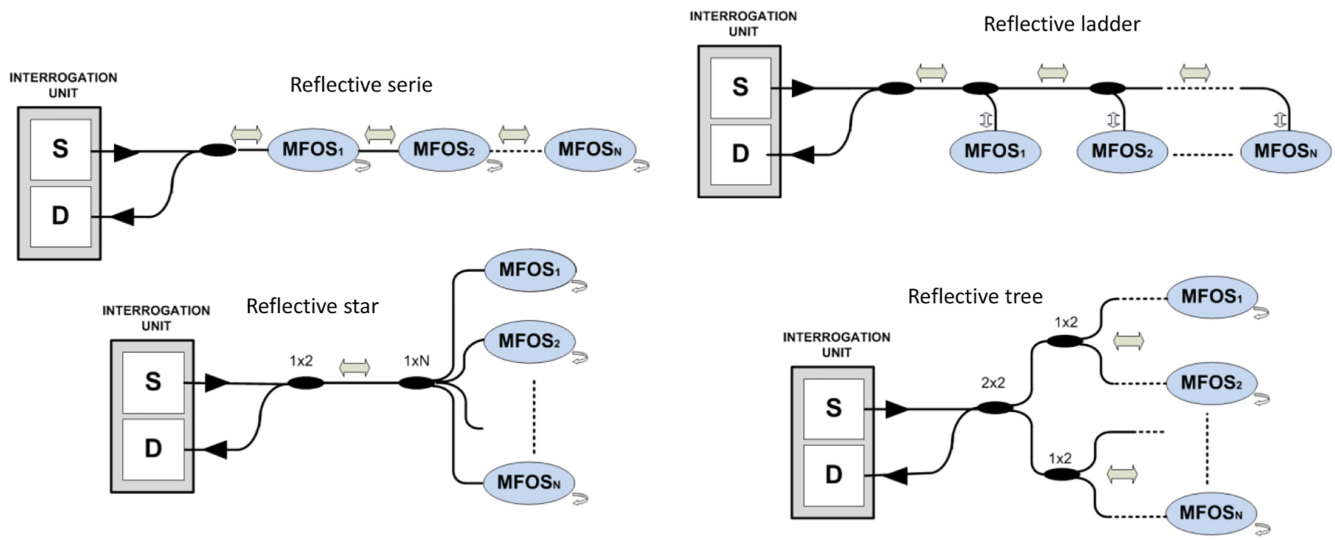

Fig. 1. All-optical reflective fiber optic sensor network architectures. S: optical source; D: optical detector; MFOS: modified fiber-optic sensor allowing self-reference.

minimize, this limitation. Such a channel must provide insensitivity to source intensity fluctuations and to variable transmission losses of the fiber link including connectors, which are often indistinguishable from transducer-caused effects, thus leading to different self-referencing strategies.

A key concept in optical fiber networks for sensors is their multiplexing capability. The modulation mechanism of the sensors is intimately related to the multiplexing technique which must be used, and vice versa, in order to interrogate several of them in the same network. As far as the type of optical signal is concerned one can make an initial distinction between networks capable of multiplexing sensors by employing optical signal's phase for the information transmission (interferometric sensors networks), or ones that are based on codifying the intensity of light (by means of some multiplexing technique) which are called the intensity sensor networks. In the case of intensity-based sensor networks, the amount of information to be addressed is usually very low and quasi-static being low-cost devices, efficient multiplexing topologies and self-referenced measurements are the most important objectives to be achieved. In this way, some multiplexing solutions for intensity-based sensors for different measurands have also been proposed [3], with plastic optical fiber as the basis for the signal distribution, trying to bridge the gap of the lack of quasi-distributed sensor multiplexing techniques as par as those proposed for FBG- or interferometric-based sensing solutions [4]. In [5] a hybrid multiplexed large capacity quasi-distributed sensing network with real-time fiber fault monitoring is proposed based on monitoring the optical intensity varying correlation spectrum of reflected FBG signals. Commercial products for fiber optic gas sensing networks have also been developed [6]. The system includes a central control unit, a fiber optic network composed of power splitters and optical multicore cables, and all-optical reflective gas sensing cells based on the evanescent field measuring principle. Due to the benefits of optical fiber networks and passive devices, it offers continuous, multipoint methane/natural gas leak detection and monitoring, from hundreds of sensing points (240 points) over a long distance (20 km). However, no self-referencing strategy is either discussed or presented.

In this paper, different self-referencing parameters for intensity-based optical sensor networks in a reflective star network topology are reported and experimentally tested. The self-referencing technique is based on the use of resonant structures and relies on the amplitude-phase conversion technique, where the optical power injected into the system is sine-waved modulated. Two electrical delay lines are deployed at the processing unit thus providing a compact remote sensor solutions and an easy-reconfigurable operation point. Using Fiber Bragg Grating (FBG) devices at the sensor head provide reflective operation and allow the use of a single fiber lead in both propagating directions of the light as well as open up wavelength-division-multiplexing (WDM) capabilities for developing quasi-distributed sensor networks.

This paper is organized as follows. Section 2 includes a detailed state-of-the-art of quasi-distributed self-referenced sensor networks from the comparative standpoint about both their architecture and addressing techniques. Including the discussion of different self-referencing techniques and some design guidelines. Section 3 includes a state-of-the-art and theoretical background of frequency-based self-referencing techniques. Describing the proposed sensor network architecture and its transfer function analysis using the digital filter theory. Section 4 contains the experimental setup as well as the self-reference property validation for addressing remote sensors on a 2-sensor proof-of-concept CWDM network with estimations about higher numbers of sensing points and remote link lengths. Finally, Section 5 presents the main conclusions.

2. Passive fiber optic quasi-distributed self-referenced sensor networks

2.1. Sensor networks architectures

The choice of the multiplexing approach depends on the requirements of the sensor network. The relative importance of parameters such as cost, noise, bandwidth and flexibility form the basis for making a selection. These parameters have many components that vary in importance depending on the application. In general, multiplexing involves the concepts of network architecture, sensor addressing and sensor interrogation. Fig. 1 shows a general view of the main topologies developed in literature [7] for implementing multiplexed fiber optic sensors or fiber sensor arrays in reflective operation thus allowing centralized remote interrogation approaches. Reflective configurations allow reducing the number of optical devices to be deployed, such as couplers or wavelength-division based multiplexers and demultiplexers. Hence, in order to make the sensor network architecture to work effectively, the remote sensing head should provide some kind of self-feedback as for instance, using Modified Fiber-Optic Sensor (MFOS), see Fig. 1. Each MFOS reflects the modulated signal carrying the sensing information to a central remote interrogation unit through the sensor network, and then demodulation takes place at the central remote interrogation unit to achieve the sensing parameters.

It is highly desirable that all the sensors in a given network return the same level of average optical power to the detection (reception)

Table 1
Comparison of the sensor network architectures shown in Fig. 1.

Topology	Number of Couplers	Optical power per Sensor[1]	Intrinsic Crosstalk
Transmissive series	0	1	Yes
Reflective series	1	1/4	Yes
Transmissive ladder	2(N − 1)	$1/N^2$	No
Reflective ladder	N	$1/4N^2$	No
Progressive ladder	2(N − 1)	$1/2^{N+1}$	No
Transmissive tree	2(N − 1)	$1/N^2$	No
Reflective tree	N − 1	$1/N^2$	No
Transmissive star	$2^{(a)}$	$1/N^2$	No
Reflective star	$2^{(b)}$	$1/4N^2$	No

(a) 1 × N coupler device (b) One 1 × 2 coupler and the other 1 × N [1] Reaching the detector.

stage. For some topologies, this can be obtained without the need of imposing special constraints on the splitting devices which is obviously a significant advantage because it permits all these devices to be equal. In addition, it is desirable that in a quasi-distributed network of *N* sensors, the number of optical devices is small and intrinsic crosstalk is not present (i.e. crosstalk related to the structure of the sensing array). It must be pointed out that the addressing scheme can introduce extra crosstalk between sensors. Table 1 compares the four topologies (series-, ladder-, tree- and star-) shown in Fig. 1 for both transmissive/reflective solutions and assuming a normalized average optical power injected into a network of *N* lossless sensors with unit transmissivity or reflectivity. The use of couplers as optical signal distribution devices is considered. However, a multiplexing approach was reported in [8] which optimizes the power budget of the network by using *N*-Coarse WDM (CWDM) devices taking advantage of the low insertion losses of such devices compared to standard optical couplers/splitters. This WDM approach, including FBGs in the MFOS, has been followed in our proposal and it will be described in detail in a further section.

From Table 1 it can be seen that different topologies show different features. For example, a lower number of optical devices is needed in both series topologies but with the disadvantage of introducing intrinsic crosstalk between sensors as the optical power injected into the network is not independently modulated in each sensor. Furthermore, the failure in the operation of one arbitrary sensor can lead to a global failure of the network, in contrast with the other topologies reported. Considering the ladder topologies it is worth to point out that the transmissive ladder topology is probably the one that has been more utilized in sensing applications [9] although progressive and reflective ladders have also been studied [10]. Table 1 also shows that ladder topologies perform no intrinsic crosstalk between sensors being the reflective ladder topology the architecture which presents a more reduced number of components whereas is penalized in terms of optical power injected per sensor, which can lead to dynamic range and sensitivity network penalties. On the other hand, tree-based topologies confirm that transmissive architectures double the number of components necessary to deploy such a network compare to the reflective option for the same performance in terms of crosstalk and average optical power per sensor. Finally, star-based topologies although performing a reduced number of optical components to be deployed and assuring a good returning optical power level per sensor, have the disadvantage of using 1 × N and N × 1 optical couplers as such devices can increase the network costs as well as being not effective in terms of the optical power budget along the sensor network.

2.2. Addressing techniques for quasi-distributed sensor multiplexing

In addition to these physical fiber wiring diagrams, a method for encoding the sensor signals is required to allow different sensors to be addressed. These methods include time-, frequency-, code-, wavelength-, polarization-division multiplexing and hybrid approaches. The optical coherence properties of the optical source can also be used to encode the sensor signals. The simplest form of multiplexing fiber optic sensor networks is by means of fiber multiplexing or Spatial Division Multiplexing (SDM) [11]. Instead of using a single optical source and a fiber per channel, fiber multiplexing uses a single optical source and divides the output among multiple sensors. This reduces the number of optical sources from *N* to one, amortizing the cost of the laser over the entire network. Consequently, the optical power available per sensor drops by a factor of *N* as well, which ultimately limits the number of sensors that can be supported per optical source. In situations where the number of fibers is not an issue this is an excellent multiplexing approach which is very flexible in terms of sensor placement and sensor configuration.

Time division multiplexing technique is based on the fact that sensor information is allocated to a particular time slot with a repetitive transmission period, i.e. time samples of the sensor outputs are interleaved in time sequence to produce a pulse train. Either optical delay coils [12] or simply the fiber itself between the sensors [13] are used to control the time-of-flight of the pulse as it passes through the network. Similar to fiber multiplexing, TDM uses a single optical source to interrogate many sensors as well as a single detector and can significantly reduce the demodulation electronics. The required duration of the input pulse is determined by the effective optical delay of the fiber connecting the fiber-optic sensor elements and repetitive pulsing of the system allowing each sensor to be addressed by simple time-selective gating of the detector output. This fact forms the main issue of the TDM technique, independently of the network architecture proposed, as well as the amount of fiber on the delay coil that must be adjusted for each sensor to account for the different delays associated with the different spacing. It is also worth to mention that in TDM networks the transducers are only illuminated a fraction of the time. This sampled system has inherent bandwidth limitations, depending on the optical delay T between adjacent sensor channels and the number of sensors in the network. Considering both terms, the maximum sample rate of a TDM network is given by Eq. (1):

$$f_m = \frac{1}{T \cdot N} \tag{1}$$

and from Nyquist's theorem the maximum signal bandwidth will be given by Eq. (2):

$$f_s = \frac{1}{2 \cdot T \cdot N} \tag{2}$$

i.e. one half of the sample rate.

The code division multiplexing (CDM) technique relies on the modulation of the interrogating optical source using a pseudo-random bit sequence (PRBS), and correlation is used to provide synchronous detection to identify specific sensor positions [14]. The received signals from the array are then encoded by delayed versions of the PRBS and correlation techniques can be used to extract the individual signals. The CDM technique can also be considered a variant of conventional TDM. However, in general, the CDM method may provide advantages in terms of power budget over TDM systems, as stronger optical signals are produced at the output.

In the frequency division multiplexing (FDM) approach, the sensor information is allocated to a particular frequency space, i.e. the sensor data is encoded on carriers, amplitude, frequency or phase modulated, of different frequencies. Such addressing scheme has been widely reported in literature concerning fiber-optic intensity-based sensors [15]. The FDM approach provides better performances with regards to the TDM approach concerning the average optical power injected per sensor which is intrinsically higher as well as simple electronic processing at the reception stage, as no fast recovery channel-circuitry is needed. Variations of such addressing method involve that the individual sensor is carried not by separate beat frequencies, but by the phase and amplitude of an RF subcarrier amplitude modulation of light source returned from the array sensor elements. Due to the differing delays between the source and detector for each sensor optical path, the resultant detector signal has a magnitude and phase which are (for a given set of sensor transmission factors) dependent on the source modulation frequency. Another technique for the multiplexing of fiber sensors based on subcarrier signal processing utilizes a series of fiber transversal filters consisting of two fibers of unequal length connected in parallel. In response to a RF intensity-modulated source, the recombined light at the filter output exhibits a series of minima when the differential delay in the two optical fiber paths corresponds to a half-integral number of cycles of the modulation frequency. This system was used to multiplex three temperature sensors [16].

Coherence multiplexing (CM) was one of the earliest method to encode the sensor information through the components of the optical carrier which have different degrees of mutual coherence with respect to some reference carrier. Due to its characteristics, coherence multiplexing has been traditionally used for multiplexing interferometric sensors [17] by using the coherence properties of the light from an optical source with short coherence length. By building the network such that only the optical path mismatch of the desired sensor is within the coherence length of the source, it is possible to ensure that only that signal will coherently interfere. All other paths through the network are sufficiently longer than the coherence length of the source that there is no coherent interference other than the desired optical path. A receiving interferometer is used to match the path mismatch of a particular sensor and provide for coherent interference. The main drawback is the poor noise performance and generally precludes the CM technique use in many practical applications thus being the number of sensors that can be supported with CM severely limited.

A further parameter of an optical system that can be used to encode optical sensor signals is polarization thus driving to the polarization-division multiplexing (PDM) approach. In this case, the sensor signals are encoded on orthogonal components of polarization of the input light source. At the detector, the received light is resolved into the two component polarization states, which can be separately detected to demultiplex the sensor outputs. The principal limitation is that only two channels of information (sensor signals) can be encoded onto a signal carrier [18].

In the wavelength division multiplexing (WDM) approach, the sensor information is allocated to a particular optical wavelength, i.e. the input light to the sensor array is divided into a number of wavelength bands/carrier that are selectively routed toward specific sensor elements, using wavelength-dependent splitters, recombiners or multiplexers. Conceptually, the WDM approach is the same as FDM with the consideration that in WDM, sensor channels must be properly spaced to avoid interchannel interference. Key system features in the WDM multiplexing sensing approach, similar to that of for optical communication systems, are capacity upgrade, transparency, wavelength routing, and wavelength switching. The WDM approach for multiplexing fiber-optic sensors can take advantage of such aforementioned features and the usefulness of this technique in sensor applications has also been demonstrated [19,20]. Such approach is theoretically the most efficient technique possible, as all the injected power from a source could be in principle directed to a particular sensor element and then onto a corresponding photodetector with minimal excess loss. This WDM technique is mostly used in fiber Bragg grating (FBG) systems for discrete sensing and to provide reflective operation [8,21–23]. In [22] a CWDM-PON based approach for self-referencing optical sensors proposed an all-optical reflective sensor network in a double star topology, using FBGs as self-referencing measurement technique, as shown in Fig. 2. The reflected optical channels were received by means of an optical circulator. This work performed enhanced sensitivity and optimized the power budget in the network by means of the CWDM devices thus increasing the number of multiplexed sensors or the distance between the light source and the remote measuring points. The maximum capacity of the sensor network is mainly determined by the spectrum bandwidth and power of light source, transmission loss of fiber link, and the channel interval of the WDM approach considered.

Each of the multiplexing approaches have fairly distinct features. Nevertheless, by blending two or more multiplexing approaches together the characteristics of the multiplexed network can be tailored to operational requirements. Multiplexing schemes that incorporate two or more approaches are generally referred to as hybrid approaches. Combining TDM and WDM is the most commonly reported topology in literature to form hybrid arrays of sensors thus providing a very flexible approach multiplexing scheme [24,25]. Even TDM and FDM to integrate self-referencing techniques [26]. Networks of several hundred sensors can be multiplexed over a single fiber lead in this manner thus achieving a quasi-distributed sensing approach.

A large number of factors determine the suitability of a sensor networking scheme for a particular application. These include the format of the sensor information, i.e. analog or digital, the optical parameter onto which the sensor information is encoded, i.e. intensity, phase, wavelength, modulation (subcarrier) frequency, etc., and the application requirements in terms of topology and performances of the network, i.e. noise level, bandwidth, dynamic range, number of fibers, flexibility (placement and configuration of the remote optical sensors), complexity, cost, etc. The relative performance of the different multiplexing schemes, excepting PDM and CDM as being minimum-deployed approaches, is tabulated in Table 2, adapted from [4]. It can be concluded that no one multiplexing scheme is the answer for all applications, but there is enough flexibility in both, the basic schemes and hybrid combinations, that an optimum scheme can be developed for any application. Furthermore, passive wavelength multiplexing technology has matured very quickly and now low loss wavelength-selective components are readily available at practically any wavelength. As a result, the WDM approach in sensor networks is an area of considerable interest.

2.3. Self-referencing strategies for optical quasi-distributed intensity-based sensors

Over the past years, intensive research and development efforts have produced a large body of fiber-optic sensor (FOS) technology [27]. Intensity modulation is one of the transducing mechanism in FOS, in which the intensity of the transmitted signal varies in accordance with the variable being measured (i.e. measurand). In general, intensity sensors are very attractive since they are simple in concept, reliable, small-sized and offer a wide range of applications at lower costs. Recent proposals include measuring the remaining fatigue lifetime of fiber reinforced polymers, by using an intensity FOS based on a bending loss configuration [28]. Their main drawback is interference from variation in losses non-correlated to the sensor modulation. The main error sources are due to the optical source and the optical fiber link elements. The thermal instability of the optical source produces source intensity fluctuations as well as wavelength emission variations. Either environmental temperature changes or heat dissipation mechanisms produce that thermal instability. The changes in the optical paths, meaning fluctuations in the intensity of the light received, are the second source of errors. Aging of the different elements of the system: source, detector, passive elements, connectors and fiber are also a problem.

To overcome this limitation and to ensure accurate measurements with optical fiber intensity modulated sensors, the implementation of a reference channel (physical or virtual) is vital. There are different self-referencing methods [29,30] to minimize the influences on the accuracy of measurements of long-term aging of optical source characteristics as well as short-term fluctuations of optical power loss in the leads to and from the transducer. Even some recent proposals combine self-referencing techniques with machine learning algorithms [31]. In any case, effective referencing of the variations associated with optical signal transmission effects needs that the reference signal either

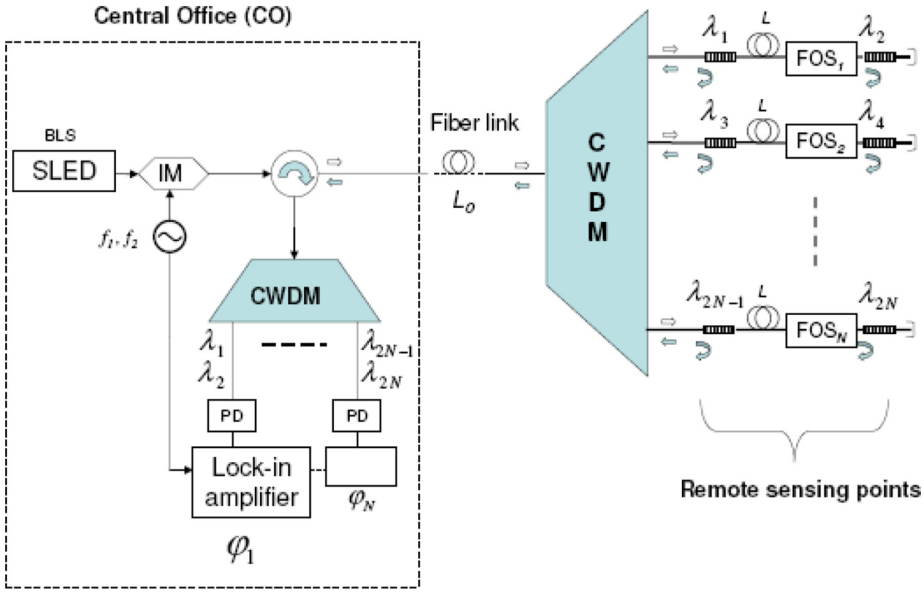

Fig. 2. Schematic of a CWDM reflective star network configuration for supporting N-self-referenced intensity fiber-optic sensors (FOS) using two FBGs and a fiber delay coil of length L, at each remote sensing point. SLED: Super-Luminiscent Erbium-Doped-Fiber Source; IM: Intensity Modulator, PD: Photodetector.

propagates in parallel with the sensing signal (measurand) or follows it very closely throughout the system. Furthermore, both signals must have the same susceptibility to all optical loss mechanisms to ensure similarity of such variations. Sensing channel and reference channel, must be separated and identified either physically or virtually by means in space, time, frequency or wavelength separation techniques, as shown in Fig. 3. These channels or signals can be distinguished following different techniques or even combining them:

- Spatial separation: using either a bundle of optical fibers or different cores in a multicore fiber (MCF) as proposed in [32], running in parallel for the reference and sensing channels. At the sensor, the measurand modulates the sensing signal whereas the reference signal is bypassed. Immunity to the optical source fluctuations is provided by using a single optical source in conjunction with a beamsplitter, a coupler or an optical circulator. The major benefit of this scheme is that can be used in almost all optical sensor types whether they are intrinsic or extrinsic, and in transmission-mode or reflection-mode. Nevertheless, there is a cost penalty associated with the use of two separate optical fibers and there is not exactly the same path among them, with less impact when using MCFs.
- Temporal separation: using a short optical pulse that circulates in an optical loop. This referencing technique produces a series of temporally-spread pulses having a similar relationship with the original pulse. However, in practice, the measurement includes the measurand plus the insertion loss of the optical loop. Subsequent temporal separation between signals allows them to propagate on a single optical fiber lead through TDM. Furthermore, both signals then exhibit similar variations with optical source fluctuations. Nevertheless, any differences between the optical signal paths reduces the efficiency.
- Frequency separation: using different carrier frequencies. It requires an electrical frequency modulation of the optical source. Subsequent frequency separation between channels allows them to propagate on a single optical fiber lead through FDM. Reference and sensing channels are electronically filtered at the reception stage. This technique allows the use of a single photodetector in reception for their demodulation. This approach also enables simultaneous parallel transmission of signals through a single optical fiber lead.
- Wavelength separation: using two separate channels comprising the reference and sensing wavelength bands. They are generated either with two separate optical sources or, extracting different slides from the same optical source. The reference and sensing channels share the optical fiber link providing an output free from variations errors by selecting two-signal wavelength bands close enough. The potential errors arising from source thermal drifts can be overcome by a proper matched of source and WDM devices' thermal behaviour. There is also a trade-off between the effective wavelength separation for both channels and the optical crosstalk induced. The nearer the channels are in wavelength, the more similar thermal behaviour but power crosstalk is higher unless high-precision demultiplexers are used.

None of the aforementioned referencing methods is fully effective against all the variations seen before. Even those incorporating advanced referencing strategies are liable to suffer from some uncertainty

Table 2
Different multiplexing schemes comparative [4]. H: High; M: Medium; L: Low; N: number of sensors in the network; I: number of WDM sources in the hybrid approach network.

Multiplexing Technique	Cost	Performance			Flexibility		
		Optical power per sensor	Noise	BW	Config	Location	Complex
None	H	1	Shot	H	H	H	L
Fiber	M	1/N	Shot	H	H	H	L
WDM	H	~1/N	Shot	H	H	H	M
TDM	L	$1/N^2$	Leakage Aliased Shot	L	L to H	L to H	M
FDM	M	1/N	Shot	H	H	H	H
Hybrid TDM/WDM	L	I^2/N^2	Leakage Aliased Shot	M	L to H	L to H	M

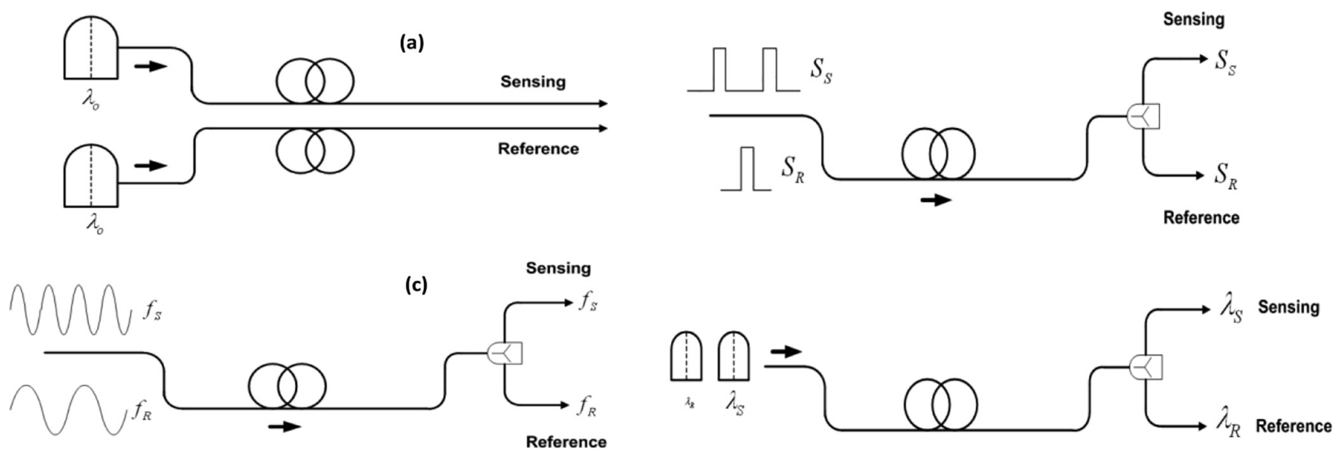

Fig. 3. Common signal separation techniques employed in referenced systems: (a) spatial separation; (b) temporal separation; (c) frequency separation; (d) wavelength separation.

of measurement. Furthermore, the number of components can be generally higher than other strategies and, consequently, less cost-effective plus the need of more complex sensing heads at the transducing point in comparison with the fiber bypass strategy, which is intrinsically very simple but non-effective if we consider the short-term fluctuations suffered by both fibers despite very similar optical paths. On the other hand, temporal separation strategies for referencing are susceptible to be not effective for the undesirable fluctuations in the intensity of the light at the common optical paths for both channels. In order to minimize such effect a solution would be to shorten the fiber loop used to generate the reference and the measurand pulses, but this improvement would lead to the use of a more complex electronics control as the temporal separation becomes shorter. However, this strategy has the advantage of using a reduced number of components in the implementation. Finally, relative to the wavelength separation strategy, although such a technique provides a similar effective referencing performance the long-term aging of the optical sources plus environmental temperature changes can produce variable wavelength emissions in such optical sources which could not be compensated. In addition to this, the real performance of optical devices such as couplers, multiplexers/demultiplexers and photodetectors implies a wavelength-dependence on their characteristics, which could influence the system performance.

As a summary, in order to allow the distinction between the intensity variation of the light at the sensing head independently of all the undesired perturbations, it is desirable to provide the same optical paths for the reference and for the sensing channels excepting in the measuring point (i.e. sensor head). Nevertheless, considering the latter premise, the use of different optical sources or photodetectors would be not overcome. Despite this fact the following considerations can be made in order to improve referencing techniques for fiber-optic intensity-based sensors:

- Preferable referencing schemes are contingent with the use of a unique optical source and a unique photodetector in order to avoid different environmental dependences (or different heating dependences) depending on the different devices characteristics. Alternatively, differential methods can be devised for simultaneous sources and receivers usually being less cost-effective.
- Both reference and sensing channels must follow the same optical path in the system except the measurement point. Consequently, referencing topologies providing the same optical fiber lead for both channels are preferable.
- The sensing head must be designed in order to properly separate the reference signal and the measurand signal as closer as possible from the point in which the transducer modulates the intensity of the light. Then, both signals must be recombined just outside the transducer. By this premise, the environmental effects in both signals can be equalized.
- No matter the referencing strategy employed, both the reference and the measuring signal must show the same dependence concerning fluctuations due to connectors, couplers, etc. in order to avoid indistinguishable measurements from transducer-caused effects.
- Desirable performances of a referencing scheme are also compatibility with optical fiber networking and scalability thus allowing the integration of multiplexed self-referencing fiber-optic sensors i a single optical fiber topology.

Most of the widely published self-referencing techniques for intensity-modulated optical sensors correspond to one of the above schemes: time-division normalization [33], wavelength normalization [34], fiber bypassing (i.e. spatial separation technique) and frequency-based referencing methods [35,36]. It is worth to point out that frequency-based strategies is particularly favorable in what concerns the minimization of the system noise. This happens because what it is monitored is the amplitude/phase of two sinewaves, i.e. the detection bandwidth can be made as narrow as practically feasible, with the consequent decrease of the system noise level.

3. Theoretical background on electrical frequency self-referencing techniques

The use of resonant structures as basis of a self-referencing intensity type sensor [37,38] is part of the amplitude-phase conversion technique. In it, the launched optical power is sine-wave-modulated with an electrical signal. In the sensing head, a fraction of that power is not affected by the measurand, constituting a reference signal. The other fraction is intensity-modulated by the measurand and constitutes the sensing signal. When both fractions are combined at the reception stage, it gives a resulting optical-power intensity sine wave. The phase of this signal, relative to the phase of the electrical signal that modulates the optical power emitted by the optical source, depends only on the optical loss induced in the sensor head, including a constant factor determined by the length of the lead/return fiber). The same latter concept can be applied to the ratio between the amplitudes of the reference and the sensing signals, respectively. The evaluation of this ratio of amplitudes and/or the phase allows obtaining information of the measurand status; independently of the optical power fluctuations that can occur outside the sensor head.

The Free Spectral Range (FSR) of the frequency response in such resonant configurations, as long as incoherent interference is carried out, can be expressed as:

$$FSR = \frac{c}{n_g \cdot L} \quad (3)$$

where c is the speed of light in vacuum, n_g is the refractive index of the fiber and L is the path difference between the two arms of the resonant structure (i.e. generally the fiber coil length inserted in such topology, although reflective Michelson topologies provide, for example, doubled effective path difference between the two arms that must be taken into account in the FSR calculation).

In the generic case, the off-resonance and resonance frequencies of the system can be determined by:

$$f_{resonance} = m \cdot FSR; \quad m = 0,1,2,... \quad (4)$$

$$f_{off-resonance} = \left(\frac{2m-1}{2}\right) \cdot FSR; \quad m = 1,2,... \quad (5)$$

On the other hand:

$$R = \frac{|H_{\text{off - resonance}}|}{|H_{\text{resonance}}|} \quad (6)$$

where R is the normalization parameter which provides the self-referencing property and $|H_{\text{off - resonance}}|$ and $|H_{\text{resonance}}|$ are the transfer function modules for the off-resonance and resonace frequencies of the fiber topology, respectively [37]. In the same way, the relative electrical phase response of the detected RF signal (relative to the phase of the electrical signal that modulates the optical power emitted by the optical source) provides a self-referenced measurement parameter.

Different sensing solutions for self-referenced interrogation of optical sensors have been proposed based on this technique by deploying different resonant structures such as Fabry-Perot [38], Mach-Zehnder [39], Michelson [40], Sagnac [41] or ring resonators [42]. Optical devices such as Fiber Bragg Gratings (FBGs) were also introduced in such topologies in order to assure a reflective operation of the sensing structure thus providing a sensitivity enhancement as the light of the sensing channel crossed twice the sensing head [43,44] as well as opening up wavelength-division-multiplexing (WDM) capabilities for remote sensing interrogation purposes. In these all-optical self-referencing technique schemes based on FBGs, a fiber coil of length L is inserted between the gratings to adjust the electrical phase difference between the reflected optical signals (reference and signal channels, respectively).

3.1. Fiber Bragg grating-based radio-frequency reflective configuration for WDM self-referenced sensor interrogation

Interrogation techniques based on FBGs, opposite from those mirror-based options, are effective approaches for addressing optical intensity sensors, because they provide reflective configurations that permit the use of a single fiber lead in both propagating directions of the light as well as opening up wavelength-division-multiplexing (WDM) capabilities. In these configurations, the transmission and reception stages can be located in a single point, namely central office (CO). From this CO the light travels to the remote sensing point through a fiber link and the reflected light, which comprises the information of the sensor-induced intensity modulation returns to the CO through the same link. A general scheme of this topology can be seen in Fig. 4.

3.1.1. All-optical approach

All-optical FBG-based radio-frequency reflective self-referencing configurations including fiber delay coils have been reported in literature, as in [8,22,45], in which the FBG is used to achieve a wavelength-based bypass self-referencing strategy. In the all-optical approach, the sensing head used two different-wavelength FBGs and a fiber delay coil of length L was inserted between the gratings to adjust the electrical phase difference between the reflected optical signals (λ_R and λ_S), see Fig. 5, achieved by using a modulated light source at frequency f.

The technique consists of an amplitude-to-phase conversion where the phase-shift, ϕ_{dif}, between the reflected light at a wavelength λ_R (reference) and λ_S(sensing) depends on the length (L) and on the modulation frequency (f) is given by[1]:

$$\phi_{dif} = \frac{2\pi}{c} \cdot n_g \cdot f \cdot 2L \quad (7)$$

where c is the speed of light in vacuum and n_g is the single-mode fiber (SMF) effective group refractive index. Eq. (7) determines the relative phase delay between the two beating signals, i.e. the RF electrical signal at the sensing wavelength (from the sensing point) with regards to the electrical signal at the referencing wavelength. From Eq. (7) it can be deduced that for a desired phase-shift value at the reception stage, the lower the frequency f the higher the (required) length of the optical fiber delay coil L. For instance, for an arbitrary fixed phase-shift value as$\phi_{dif} = 0.5\pi$ the fiber delay coil length results in 5.2 km for a modulation frequency of $f = 5$ kHz, being quite long for real-field deployments with multiple sensors.

At reception, due to the electrical beating of both optical reflected signals at the detector for a single sensor, the resulting phase of the impinging signal can be expressed as (further details of the mathematical framework are reported in [45]):

$$\phi = \arctan\left[\frac{(m_s/m_r)\beta + \cos(\phi_{dif})}{\sin(\phi_{dif})}\right] \quad (8)$$

being $m_s$and m_r the source modulation indexes at wavelengths λ_S and λ_R, respectively. β reflects the transducer losses being defined as the ratio between the optical carrier power at wavelengths λ_S and λ_R, respectively, with $\beta \in [0, 1]$. This β parameter depends on the reflection coefficients of the two FBGs, the transducer response squared (optical signal λ_S passes through the transducer twice due to the reflective scheme as aforementioned) as well as the losses in the delay line and additional splices/connectors within the FOS topology.

From Eq. (8), the output phase parameter depends only on the optical signals phase difference (ϕ_{dif}), the modulation index ratio ($^{m_s}/_{m_r}$) and the β parameter being, consequently, insensitive to power fluctuations anywhere at the link. The phase difference will be a constant factor once the modulation frequency and the phase-shift between both signals are fixed.

The following figure shows the corresponding digital filter model of the all-optical configuration described in Fig. 5, as reported in [22] (Fig. 6).

All-optical signal processors based on fiber-optic technology were reported in order to overcome the bandwidth constraints of microwave and RF signal filters. Incoherent regimes of operation can be assured when the time delays in the optical paths are much higher than the coherence time of the optical sources employed, given always positive coefficients for such filters [46]. On the other hand, when the time delays in the optical paths are comparable to the coherence time of the optical sources, the optical phase relations between the different ports are deterministic and coherent filters can be achieved [47,48] providing great design flexibility.

3.1.2. Electro-optical approach

As an upgrade from an all-optical FBG-based reflective configuration for self-referenced measurements a novel electro-optical design, which avoids the need for fiber delay coils was firstly reported in [49] thus achieving compact sensor heads, and afterwards extended to a WDM sensor network with reconfigurable characteristics [50] based on the amplitude-frequency conversion transducing technique. By employing electrical filters at the reception stage, it is possible to achieve arbitrary modulation frequencies as the self-referencing parameters defined for this electro-optical topology depend only on the phase-shifts selected at the reception stage. This provides compact sensing points as no fiber delay coils are needed in the sensing heads, and flexibility as the electrical phase-shifts (in the electrical domain) at the reception

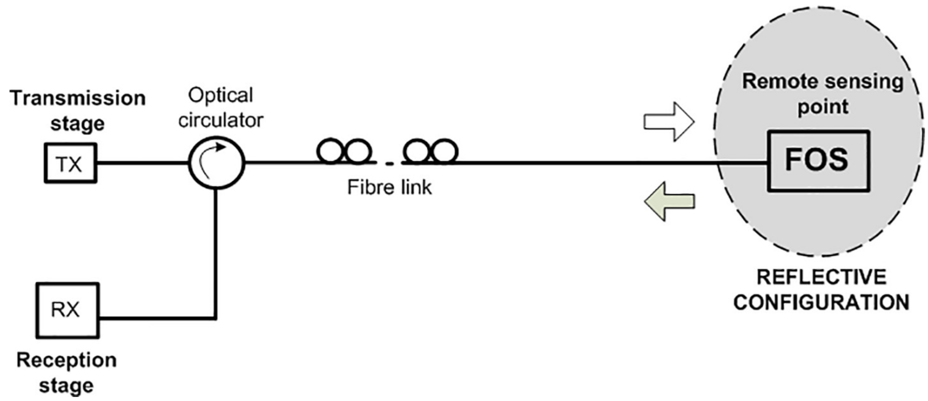

Fig. 4. General scheme of a bidirectional fiber link for remotely addressing fiber-optic intensity sensors (FOS) with a reflective configuration in the sensing point.

stage can be easily modified. This changes in a rapid fashion the performance of the defined self-referencing parameters. Furthermore, the optical power modulation of the sensor at the remote sensing point can be related to the coefficients of the filter structure thus encoding the filter response either in magnitude or in phase and performing self-referenced measurements.

The proposed electro-optical fiber-optic topology for addressing N intensity-based optical sensors placed within two FBGs is shown in Fig. 7 as well as the detailed resulting digital filter schematic of the complete sensor topology, see Fig. 8 where the dashed and solid lines correspond to the electrical and optical domain respectively.

An intensity modulator (IM) modulates at a single frequency f the light from a broadband light source (BLS), or alternatively from two optical signals with optical power density around the two reference and sensing wavelengths. In the remote sensing point, the optical signal is sliced in wavelength and reflected by two FBGs at the remote sensing point. The central wavelengths of the FBGs placed before and after the fiber-optic sensor (FOS_i) are named λ_{Ri} (reference wavelength) and λ_{Si} (sensing wavelength), respectively. The sensor power modulation is defined as H_i. The broadband optical circulator receives the reflected multiplexed optical signal with the sensor information. At reception, a CWDM device demultiplexes the optical signal from each sensor that are delivered to an array of N photodetectors (PD) and a lock-in amplifier at the reception stage. It is worth to note that if N lock-in amplifiers are available (one amplifier for each remote sensing point) all sensor channels can be simultaneously interrogated but leading to a less compact and a high-cost solution at the reception stage. Then two electrical phase-shifts (Ω_1 and Ω_2) are applied to the RF modulating signal at both wavelengths thus achieving a delay line filter deployed in the electrical domain but with a coefficient, β_i, which depends on the optical power modulation H_i in the sensing point. Those electrical phase-shifts $D(\lambda_{Ri}) = e^{-j\Omega_1}$ and $D(\lambda_{Si}) = e^{-j\Omega_2}$ are applied to the RF modulating signal and provide a flexible and easy-reconfigurable operation point of the remote intensity sensor.

The response of the remote sensing configuration and the measurement technique realized for both self-referencing parameters for a generic remote sensing channel i containing both corresponding wavelengths λ_{Ri}, λ_{Si} and the electrical phase shifts Ω_1, Ω_2 is following described through the Z-transform formalism. The system output in the time domain, see Fig. 8(b), can be expressed as follows:

$$p_0(t) = \alpha_i \cdot (p_{Ri}(t) + \beta_i \cdot p_{Si}(t)) \tag{9}$$

with

$$\alpha_i = m_{Ri}.\ R(\lambda_{Ri}).\ d_{Ri} \tag{10}$$

$$\beta_i = \frac{m_{Si}.\ R(\lambda_{Si}).\ d_{Si}}{m_{Ri}.\ R(\lambda_{Ri}).\ d_{Ri}} H_i^2 \tag{11}$$

where m_{Ri}, $R(\lambda_{Ri})$ and d_{Ri} are the RF modulation index, the reflectivity of the FBG and the photodetector response at the reference wavelength λ_{Ri} for the generic remote sensing point i, respectively, and m_{Si}, $R(\lambda_{Si})$ and d_{Si} are the respective similar parameters for the sensor wavelength λ_{Si}. From now on, the parameter β_i will be considered the power modulation parameter of the self-referencing configuration whose relationship with the transducer intensity modulation is ruled by Eq. (11).

The time domain signals of sensing channel i at modulation frequency f, $p_{Ri}(t) = \cos(2\pi \cdot f \cdot t - \Omega_1)$ (reference signal) and $p_{Si}(t) = \cos(2\pi \cdot f \cdot t - \Omega_2)$ (sensing signal), can be studied under steady-state analysis using phasor transform of the corresponding sinusoidal signals:

$$\begin{aligned} P_{Ri} &= P_{in} \cdot \alpha_i \cdot \exp(-j \cdot \Omega_1) \\ P_{Si} &= P_{in} \cdot \alpha_i \cdot \beta_i \cdot \exp(-j \cdot \Omega_2) \end{aligned} \tag{12}$$

The output signal response as a phasor P_0 can be analyzed using the previous phasors and the resulting time-domain signal at frequency f (Hz) can be recovered by obtaining the real part of $P_0 \cdot \exp(-j \cdot 2\pi \cdot f \cdot t)$.

The expression of the normalized system output as a phasor is given by:

$$H_0 = \frac{P_0}{P_{in}} = \alpha_i' \cdot [1 + \beta_i \cdot \exp[-j \cdot (\Omega_2 - \Omega_1)]] \tag{13}$$

being $\alpha_i' = \alpha_i \cdot \exp(-j \cdot \Omega_1)$.

The expression of H_0 can be directly identified with the transfer

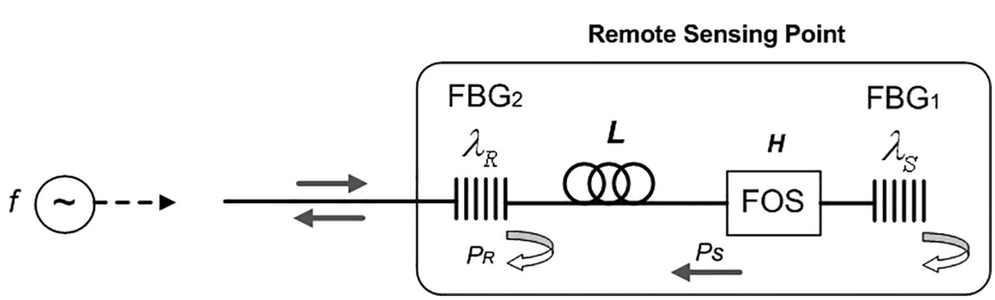

Fig. 5. Reflective configuration in the remote sensing point for self-referencing, using a MFOS made of a FOS, two FBGs and a fiber delay line.

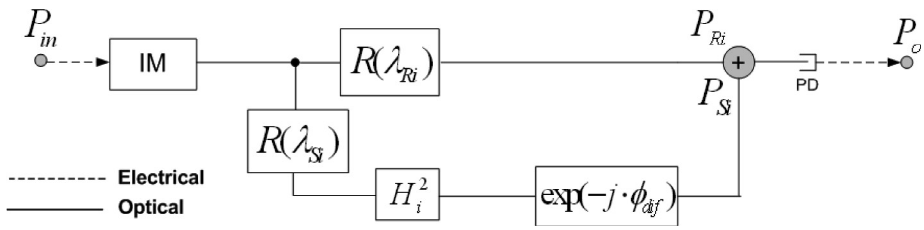

Fig. 6. Filter schematic for all-optical FBG-based self-referencing configuration of Fig. 6. IM: Intensity Modulator.

function of a digital Finite Impulse Response (FIR) filter in the Z-Transform domain as follows:

$$H_0(z) = \alpha_i'\cdot(1 + \beta_i\cdot z^{-1}) \tag{14}$$

where $z^{-1} = \exp(-j\cdot\Omega)$ with $\Omega = \Omega_2 - \Omega_1$.

Using the transfer function $H_0(z)$ in the Z-Transform domain permits an easy study of the system frequency response in terms of generic design parameters. The phase shift difference $\Omega = \Omega_2 - \Omega_1$ between the time domain reference and sensor signals represents, at the same time, the angular frequency of the digital filter $H_0(z)$.

The sensor loss modulationH_i, which depends on the measurand, is encoded in the transfer function of the self-referencing configuration by means of the parameter β_i. In Equation (11) it appears H_i^2 as the light crosses the sensor twice. From Eq. (14) it can be seen that β_i is a zero of the transfer function. So a zero transmission occurs when the following two conditions are fulfilled:

$$\beta_i = 1 \tag{15}$$

$$\Omega = \Omega_2 - \Omega_1 = \pi\cdot(2k - 1) \text{ for integer } k \tag{16}$$

The normalized magnitude response and the phase response versus the angular frequency Ω of the digital filter model of Fig. 8 are shown in set of Fig. 9 for different values of β_i. A symmetrical magnitude shape and an anti-symmetrical phase shape can be seen with regards to $\Omega = \pi$; and a zero transmission takes place at condition $\Omega = \pi$ for $\beta_i = 1$.

For a single sensor, the sensor-induced power modulation H_i induces module (magnitude) and phase variations in the output voltage V_O at reception from the optical-to-electrical conversion on the photodiode and from the current-to-voltage transimpedance stage. Both the module ratio between two different arbitrary phase-shifts and the phase response can be used as self-referencing measurement parameters. On the one hand the parameter R_i, which is defined as the ratio between voltage values at the reception stage for different electrical phase-shifts and on the other hand the output phase ϕ_i of the electrical signal for different electrical phase-shifts at the reception stage. The expression of both measurement parameters can be seen in Eq. (17) and Eq. (19), respectively.

Considering the definition ofR_i as the ratio between both reflected optical powers this parameter can be expressed as

$$R_i = \frac{V_O(f, \Omega_2)}{V_O(f, \Omega_1)} = \frac{M(f, \Omega_2)|_{\Omega_1=0}}{M(f, \Omega_1)|_{\Omega_2=0}} = \frac{[1 + (\frac{2\beta_i}{1+\beta_i^2})\cos\Omega_2]^{1/2}}{[1 + (\frac{2\beta_i}{1+\beta_i^2})\cos\Omega_1]^{1/2}} \tag{17}$$

where

$$M(f, \Omega_1, \Omega_2) = \alpha_i(1 + 2\beta_i\cos\Omega_i + \beta_i^2)^{1/2} \tag{18}$$

From Eq. (18), the expression of the magnitude corresponding to sensor i at angular frequencies Ω_1, $\Omega_2$can be written as a function of $\Omega_i = \Omega_2 - \Omega_1$.

The expression of the other parameter, the output phase ϕ_i for different electrical phase-shifts corresponding to sensor i can be written as:

$$\phi_i = \arctan\left[\frac{-(\sin\Omega_1 + \beta_i\sin\Omega_2)}{(\cos\Omega_1 + \beta_i\cos\Omega_2)}\right] \tag{19}$$

For a fixed value of the modulation frequency and the electrical shifts, both measurement parameters, R_i and ϕ_i, of the remote sensing point i depend only on β_i. Eq. (11) shows that β_i is insensitive to external power fluctuations in the optical link between the sensing point and the transmission stage. Moreover, both self-referencing parameters can be determined for any pair of values of angular frequencies (Ω_1, Ω_2) providing flexibility to the measurement technique at the remote sensing network for any desired operation point.

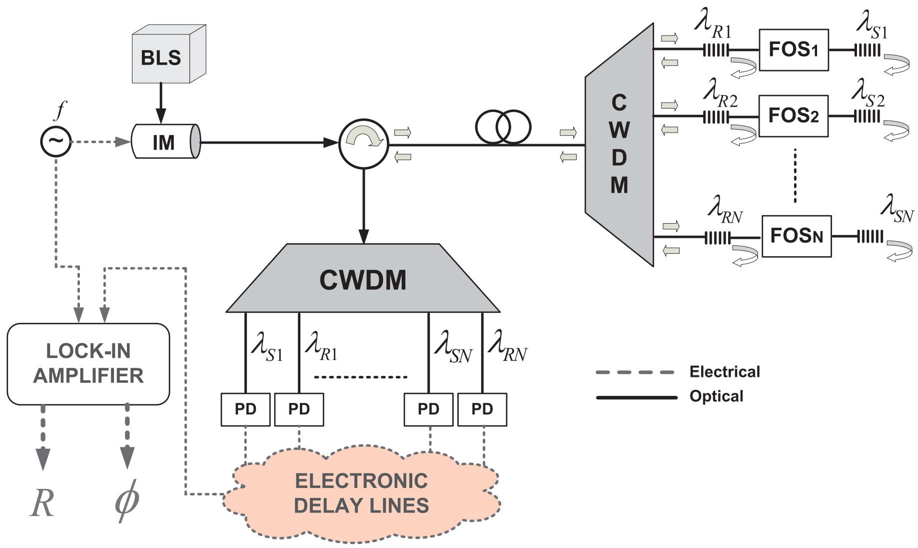

Fig. 7. Schematic of the proposed electro-optical CWDM network for supporting N self-referenced optical fiber intensity sensors (FOSi, i = 1,…,N). BLS: Broadband Light Source, IM: Intensity Modulator, PD: Photodetector, FOS: Fiber Optic Sensor.

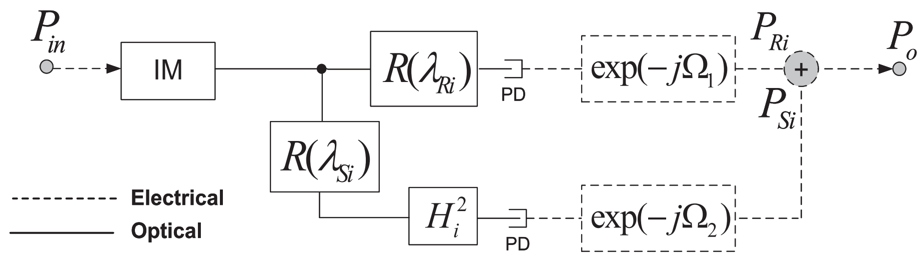

Fig. 8. Filter model of the configuration for a remote sensing point with no fiber delay coil and electrical phase-shifts at the reception stage. IM: optical intensity modulator, PD: photodetector.

4. Experimental results and discussion

The electro-optical network configuration shown in Figs. 7 and 8 was implemented using SMF leads in order to experimentally validate both self-referencing parameters simultaneously, for two remote sensor channels. An Erbium-doped broadband light source modulated at f = 10 kHz by an acousto-optic modulator was employed to launch optical power into the configuration through the broadband circulator. A pair of low-cost FBGs were used for each remote sensing point. Their central wavelengths were $\lambda_{R1} = 1530.1nm$, $\lambda_{S1} = 1535nm$ for FOS_1 and $\lambda_{R2} = 1550.3nm$, $\lambda_{S2} = 1552.1nm$ for FOS_2, compatible with standard ITU G.694.2 for CWDM networks. Two single-mode tapers operating as micro-displacement sensors were placed between each pair of FBGs with sensor loss modulations H_1 and H_2, respectively. A picture of the experimental setup for one sensing device is shown in Fig. 10(a). Calibration curves of relative optical power versus displacement as well as versus the corresponding applied strain are depicted in Fig. 10(b) for the two sensing devices. In order to test the hysteresis of the sensors, two sets of measurements, marked as *fwd* (forward) and *bkw* (backward), are taken for increasing and decreasing values of the displacement, respectively. The tapers were obtained by elongation of SMF using a semi-automatic fabrication process. Once the tapers were fixed onto a micro-positioning system, the optical loss of the tapers were sensitive to the compressive displacement between the two fiber ends. Due to the tolerance of the elongation and positioning semi-automatic processes for obtaining the fiber sensors, there is a difference between sensors' lengths and their sensitivity to mechanical displacement. The reflected signals are demultiplexed by a CWDM demux, collected by InGaAs photodetectors and phase-shifted by the electronic delay filters. Finally the output P_O for each sensing device, measured directly from the electrical signal Vo detected at the reception stage, was connected to a lock-in amplifier to obtain both self-referencing parameters R_i and ϕ_i (i = 1, 2) for each FOS_i. A detailed experimental setup scheme at reception is shown in Fig. 11, where both reference and sensing channels referred to one FOS are within the same CWDM channel and additional FBGs and optical circulators are employed to slice the contribution for each signal.

We first validated the theoretical model described in Section 3.1.2. Different calibration curves of the system and both self-referencing parameters versus β for FOS_1 were measured for different phase-shifting values showing a good agreement between theory and measurements, see Fig. 12. For both parameters, measurement deviations were at least one order of magnitude below from the mean value.

In order to validate that both measurement parameters, R and ϕ, were insensitive to power fluctuations of the modulated optical source as well as to undesirable losses at any point in the optical fiber link, the self-reference property was tested. We use the same experimental set-up shown thus emulating unexpected power losses along the optical path linking the optical source with the remote sensing area. To do so, a single-mode variable optical attenuator (VOA) was located at the transmission stage between the BLS and the broadband circulator in the experimental setup of Fig. 7. Fig. 13(a) and (b) show, respectively, that there was no correlation between the measurements of both self-referencing parameters (R_1 and ϕ_1, related to FOS_1) and the induced power attenuation with the VOA thus providing the self-reference property to the remote sensor network. In addition, it is also demonstrated that there is no influence of the phase-shift$\Omega = \Omega_1 - \Omega_2$ concerning the self-reference property. Similar results were obtained for the self-referencing parameters regarding FOS_2.

In order to test the crosstalk between two sensors operating in

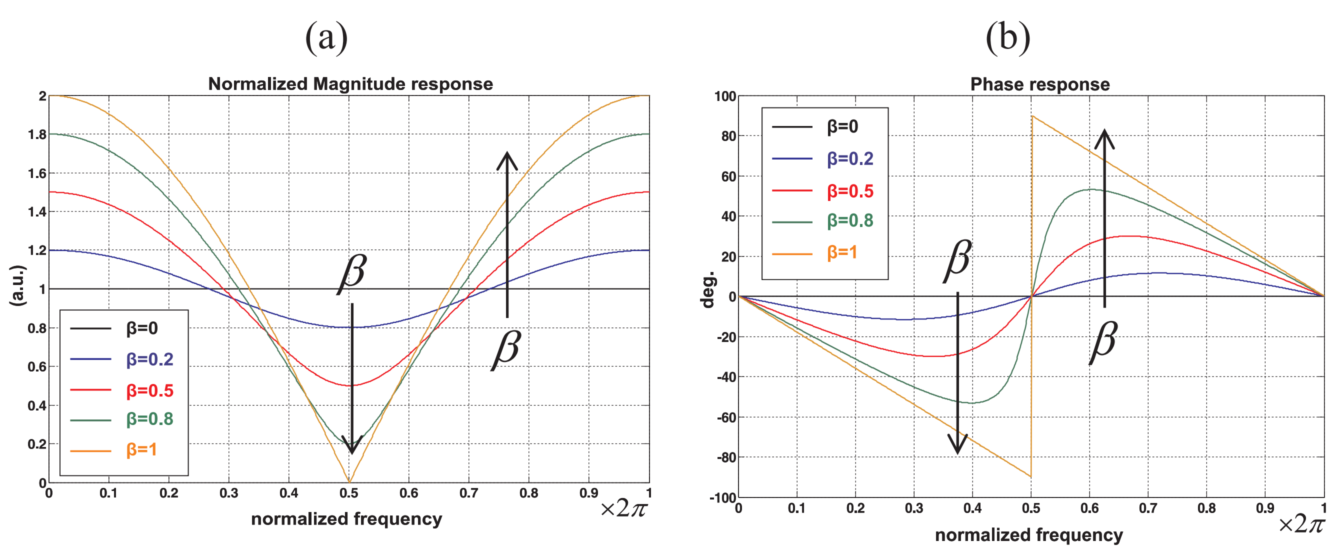

Fig. 9. Normalized response of the transfer function of the self-referencing configuration versus angular frequency for different values of β_i. (a) magnitude response; (b) phase response.

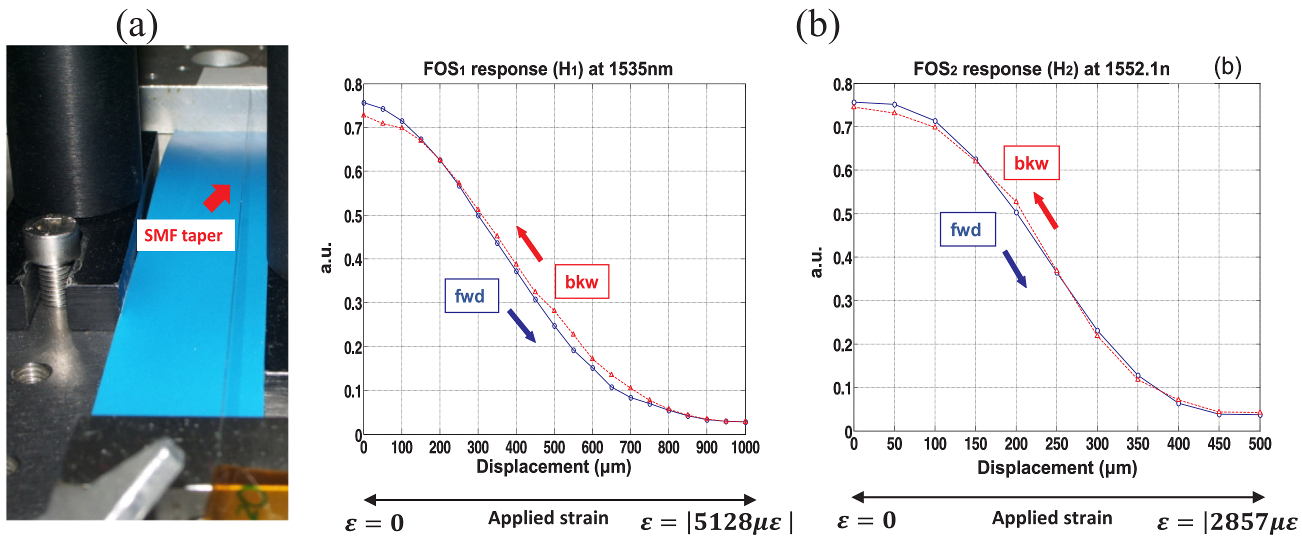

Fig. 10. (a) Picture of the setup of one tapered SMF sensing device acting as a displacement sensor. (b) Calibration curves of both sensing devices used for the self-referencing experiments.

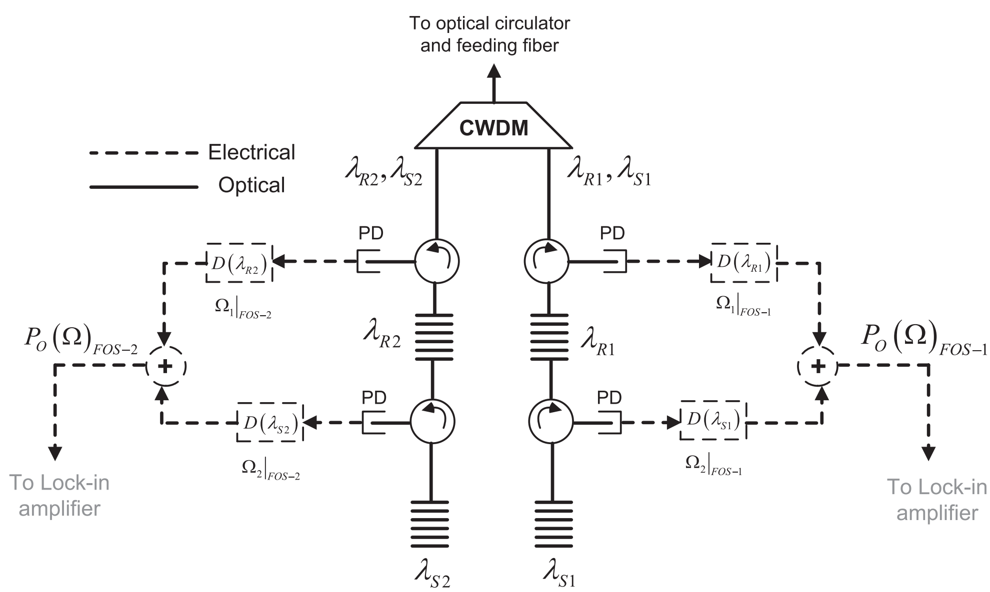

Fig. 11. Detailed experimental setup at reception unit. PD: photodetector.

adjacent CWDM channels, several measurements of the self-referencing parameters R_1 and ϕ_1 (FOS_1) were taken for different values of the sensor losses modulation β_2 (FOS_2) and in different operation points of Ω_i, as shown in Fig. 14(a) and (b). Similar results were obtained when monitoring R_2 and ϕ_2 (FOS_2) when changing β_1 (FOS_1). In both cases, no crosstalk was induced due to changes in any sensor loss modulation so both sensors can be interrogated simultaneously without mutual interference.

One of the main benefits of the electro-optical topology is its inherent flexibility in terms of selecting specific operation points of the network for each remote sensing point thus being able to design phase-shift configurations to achieve target behaviors of the measurement parameter such as linearity or sensitivity, see details in [50]. There is an extension of this electronic delay-line implementation in [51] where the use of virtual instrumentation to define virtual delay lines was proposed while preserving the self-referencing and performance characteristics of the proposed self-referencing remote sensing interrogation topology. The solution leaded to an even more compact solution, which was demonstrated in [52]. The new resulting filter model of the proposed topology is depicted in Fig. 15.

Using the same set-up, with this BLS is possible to interrogate 16 sensors at remote site around 65 km away, using the data provided in [53]. This means, considering 1 dB and 4.3 dB insertion losses at circulators and 16-channel CWDM MUX/DEMUX devices respectively, optical fiber losses of 0.2 dB/km, 99% FBG reflectivity and FOS insertion losses for the full measurement range up to 8 dB, from Fig. 10. A BLS power of −10dBm per channel assuming 10 nm-bandwidth sensing FBGs and a receiver sensitivity of −74dBm are considered. This link length reduces to half for the worst-case channel placed at 1270 nm.

The total number of channels upgrades by introducing DWDM channels in the C and L bands thus scaling the proposed sensor network to a quasi-distributed sensing approach, but at the expenses of reducing the remote site location distance and increasing the number of elements. We estimate a feasible upgrade up to a 48-sensor network DWDM approach with 25 km of reaching distance for remote interrogation.

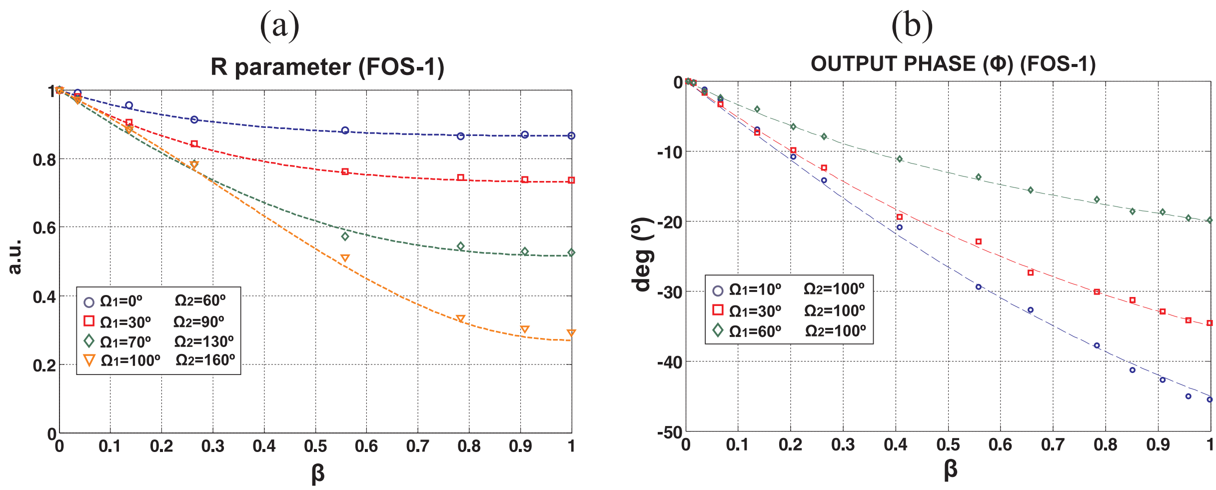

Fig. 12. Measurements and theoretical validation (dashed lines) of FOS_1 versus β for different phase-shift at the reception stage. (a) R parameter; (b) output phase ϕ parameter.

An application to individually monitoring optical power loss of drop fibers in access WDM-PON systems was reported in [53] based on the self-referencing technique described and employing coloured reflectors. Recent approaches have also demonstrated the feasibility and compatibility of this remote interrogation technique for in-service monitoring of Dense WDM-PON systems [54] by employing colorless reflectors and cyclic arrayed waveguide grating devices and with response times much greater compared to other monitoring techniques that employ optical time domain reflectometers.

5. Conclusions

A self-referencing electro-optical FBG-based reflective topology for remote interrogation of fiber-optic intensity sensors has been analyzed. The topology includes the utilization of a resonant structure for each single sensor as the basis of the self-referencing property by analyzing the ratio between two signals (reference channel and sensing channel) or their respective phase difference.

The electro-optical approach for deploying delay-lines provide more compact remote sensor-heads and an easy-reconfigurable operation point. Moreover by including two delay lines implemented in the electrical domain arbitrary modulation frequencies can be set and phase shift reconfiguration can overcome tolerance errors permitting an easy-reconfigurable operation of the network. It is possible to select any operation point for each remote sensor by means of their associated electrical phase-shifts at the reception stage, in terms of linearity response, sensitivity, resolution or another system property depending on specific requirements. The transfer function of the remote sensing configuration using the digital filter theory and following the Z-transform formalism has been analyzed, and the definition of both self-referencing measurement parameters is addressed as well. There are two self-referencing parameters for any remote sensing point of the multiplexed sensor network: a) the ratio between voltage values at the reception stage for different electrical phase-shifts, and b) the output phase at the reception stage for different electrical phase-shifts.

Measurements validating the theoretical model have been reported. A two intensity-based fiber-optic sensor network has been implemented to validate the performance of both parameters as a proof-of-concept for an extended quasi-distributed sensor network solution. Two tapered SMFs acting as micro-displacement sensors are developed and characterized to this purpose. The self-reference property for both parameters has been also validated by emulating undesirable link losses up to 12 dB. There was no crosstalk when the two sensors operating within the same CWDM channel were simultaneously interrogated. Scalability to DWDM-based networks to increase the number of addressed sensors is easily envisaged but at the cost of reducing the remote sensing location distance due to increasing power budget penalties arising in the system by the introduction of additional DEMUX devices.

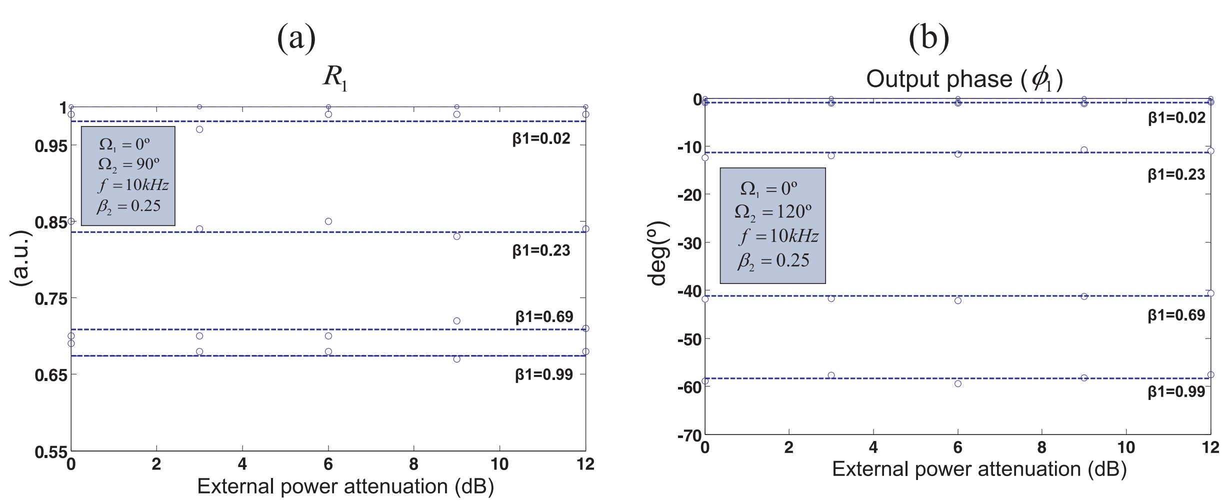

Fig. 13. Self-reference test vs power variations and changing β_1 with $\beta_2 = 0.25$: (a) R_1 (b) ϕ_1.

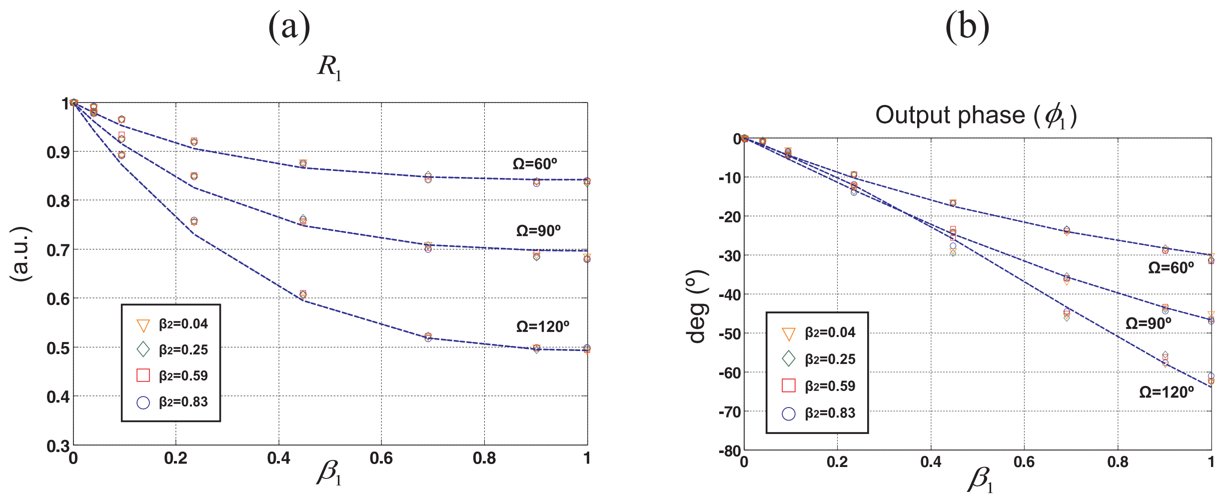

Fig. 14. Measurements of R_1 (a) output phase ϕ_1 (b) vs β_1 for different β_2.

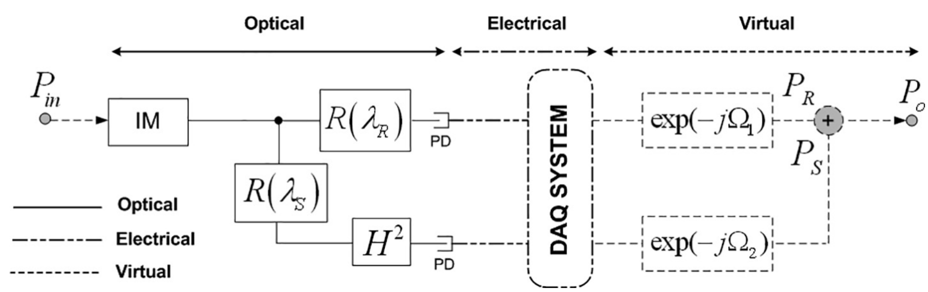

Fig. 15. Filter model of the proposed topology for a generic remote sensing point with two virtual delay lines, after acquisition, at the reception stage. IM: Intensity Modulator, PD: Photodetector.

CRediT authorship contribution statement

D.S. Montero: Investigation, Software, Writing - original draft, Writing - review & editing. **C. Vázquez:** Investigation, Formal analysis, Funding acquisition, Supervision, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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