Coarse WDM networking of self-referenced fiber-optic intensity sensors with reconfigurable characteristics

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Abstract: A CWDM network operating in reflective configuration for multiplexing remote Radio-Frequency (RF) self-referenced fiber-optic intensity sensors is analyzed and experimentally investigated. In the described approach, the use of fiber Bragg gratings as spectral selective mirrors allows to implement delay lines in the electrical domain, achieving more compact sensor-heads and easy-reconfigurable sensing points. Two measurement parameters for the sensing heads are defined and comparatively studied in terms of design parameters, linearity, sensitivity and resolution. The proposed sensor configuration is modeled following the Z-transform formalism, which permits an easy analysis of the system frequency response. Experimental results are presented, showing the characterization of the network performance and considering the properties of sensor self-referencing as well as sensor crosstalk.

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Intrinsically safe fiber-optic intensity-based sensors (FOS) have been developed for a wide variety of physical magnitudes such as temperature, pressure, humidity and displacement [1–4] providing an optical intensity modulation signal as the measurement. These fiber optic intensity sensors can be easily integrated in WDM networks, including those based on Fiber Bragg Gratings (FBG) operating in reflective configuration [5,6], for remotely addressing multiple sensing points and providing an effective strategy for exploiting fiber links with a single fiber lead. However, the main drawback of these intensity-based optical sensors is interference from variation in losses non-correlated to the sensor modulation, so some strategy must be integrated in the sensor network or, recently, even integrated in the remote sensing point to overcome those undesirable power fluctuations [7].

Different configurations providing self-referencing techniques to solve this disadvantage have been reported employing all-optical layouts in the sensor-head with interferometric schemes such as Michelson [8,9] or Sagnac [10], ring resonators schemes [11,12] or non-compact fiber delay coils [6,13]. For instance, in [6] identical fiber coils of 450m are emplaced at each sensing point. These fiber delay coils at all sensing points must be identical in order to share the two modulation frequencies at the transmission stage for all the sensors; otherwise the operation point of the measurement technique would be different for each sensor, which is not a desirable situation. In order to avoid this restriction it is possible when considering the utilization of spectrally selective mirrors to replace the long fiber coils with electrical filters at the reception stage obtaining a novel electro-optical topology of the remote sensor network thus achieving:

- Arbitrary modulation frequencies: it is needed only one modulation frequency whose value can be chosen depending on the application. The self-referencing parameters defined for this electro-optical topology depend only on the phase-shifts selected at the reception stage.
- Compact sensing point: no fiber delay coils or complex schemes are needed in the sensing points being the performance of the all-optical configurations preserved. This is because the behavior of the self-referencing parameters versus sensor losses modulation at the sensing points depends only on the electrical phase-shifts configured at the reception stage.
- Flexibility: the behavior of the self-referencing technique can be modified in a single point and in an easy and flexible way just by changing the electrical phase-shifts (in the electrical domain) at the reception stage.

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.

In this paper, a self-referenced electro-optical FBG-based CWDM fiber-optic intensity sensor network is proposed. This configuration consists on a reflective star network topology for multiplexing and interrogation of \( N \) quasi-distributed self-referencing remote sensing points although the scalability of the topology could permit a higher amount of addressed sensor channels by employing devices such as arrayed-waveguide gratings (AWG) for dense WDM (DWDM) instead of CWDM devices if required. It is based on a configuration previously reported in [14] but using two electrical phase-shifts, giving flexibility to the configuration in terms of selecting the operation point or correcting fabrication tolerances. Two measurements parameters are defined using those two electrical phase-shifts, one based
on phase measurements and another based on amplitude measurements. Both novel topologies are analyzed in terms of their self-reference property, crosstalk between sensors, sensitivity, linear response and resolution. In section 2 the sensor network architecture is presented including the transfer function analysis of the remote sensing configuration using the digital filter theory and the definition of both self-referencing measurement parameters. Section 3 contains the performance of an experimental CWDM 2-sensor network confirming the insensitivity to external power fluctuations and the no correlation between two sensors operating in adjacent CWDM channels when they are simultaneously interrogated. Section 3 also contains the sensitivity, the linearity and resolution analysis of the performance of both measurement parameters defined for this topology. Finally, the main conclusions of this work are reported in section 4.

2. Theory

The proposed electro-optical fiber-optic topology for remotely addressing $N$ intensity-based optical sensors placed within two Fiber Bragg Gratings (FBGs) is shown in Fig. 1.

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

A broadband light source (BLS) is modulated at a single frequency $f$, thus avoiding the flicker noise (1/f) effect in the measurements at the reception stage. After the transmission stage, a broadband circulator is located in order to launch the modulated broadband signal into the remote sensing points. Each remote sensing point consists on a pair of FBGs placed before and after the fiber-optic sensor (FOS) with central wavelengths $\lambda_{R_i}$ (reference wavelength) and $\lambda_{S_i}$ (sensing wavelength), respectively. The broadband optical circulator receives the reflected multiplexed optical signal with the sensor information. The optical signal is demultiplexed by a CWDM device and delivered to an array of $N$ photodetectors (PD) and a lock-in amplifier at the reception stage. If $N$ lock-in amplifiers are available (one amplifier for each remote sensing point) all sensor channels can be simultaneously interrogated thus leading to a less compact and a high-cost solution at the reception stage.
In this section, the response of the remote sensing configuration and the measurement technique realized for both self-referencing parameters are simultaneously considered for a generic remote sensing channel $i$. The electro-optical topology with electronic delay lines proposed for a single generic remote optical sensor $i$ is shown in Fig. 2(a). The digital filter schematic of the complete sensor topology is shown in Fig. 2(b). Let $H_i$ be the sensor loss modulation. In the reception stage, electrical phase-shifts $D(\lambda_{Ri}) = e^{-\beta_i}$ and $D(\lambda_{Si}) = e^{-\beta_i}$ are applied to the RF modulating signal providing a flexible and easy-reconfigurable operation point of the remote intensity sensor. The delay line filters are deployed in the electrical domain but with a coefficient $\beta_i$ which depends on the sensor loss modulation $H_i$ in the sensing point.

The response of the remote sensing configuration and the measurement technique realized are considered for a generic sensor channel $i$ containing both corresponding wavelengths $\lambda_{Ri}$, $\lambda_{Si}$ and the electrical phase shifts $\Omega_1$, $\Omega_2$.

The system output in the time domain, see Fig. 2(b), can be expressed as follows:

$$p_o(t) = \alpha_i \cdot \left( p_{R_i}(t) + \beta_i(t) \cdot p_{S_i}(t) \right)$$

with

$$\alpha_i = m_{R_i} R(\lambda_{Ri}) d_{R_i}$$

$$\beta_i = \frac{m_{S_i}}{m_{R_i}} R(\lambda_{Ri}) d_{R_i} H_i$$

Fig. 2. (a) Point-to-point self-electro-optical configuration for a generic remote sensing point. 
(b) Filter model of the configuration for a remote sensing point with two electrical phase-shifts at the reception stage.
where $m_R$, $R(\lambda_{m})$ and $d_R$ are the RF modulation index, the reflectivity of the FBG and the photodetector response at the reference wavelength $\lambda_{m}$ for the generic remote sensing point $i$, respectively, and $m_S$, $R(\lambda_{s})$ and $d_S$ are the respective similar parameters for the sensor wavelength $\lambda_{s}$.

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

$$
P_{ir} = P_{in} \cdot \alpha_i \cdot \exp(-j \cdot \Omega_i)
$$

$$
P_{is} = P_{in} \cdot \alpha_s \cdot \beta_i \cdot \exp(-j \cdot \Omega_s)
$$

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 $P_0 \cdot \exp(-j \cdot 2\pi f \cdot t)$.

Examining the expression of the normalized system output as a phasor, it is obtained:

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

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

The expression of $H_0$ can be directly identified with a digital Finite Impulse Response (FIR) filter in the Z-Transform domain as follows:

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

where $z = \exp(-j \cdot \Omega)$ 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, as reported in [14]. With this approach, 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 modulation $H$, which depends on the measurand, is encoded in the transfer function of the self-referencing configuration by means of the parameter $\beta_i$. In Eq. (3) it appears $H^2$ due to the reflective operation of the sensing structure (the light crosses twice the sensor).

The normalized magnitude response and the phase response versus angular frequency $\Omega$ of the digital filter model of Fig. 2(b) is shown in Fig. 3(a) and Fig. 3(b), respectively, for different values of $\beta$. A symmetrical magnitude shape and an anti-symmetrical phase shape can be seen with regards to $\Omega = \pi$. 


At this point, two measurement parameters can be defined for the remote sensing point shown in Fig. 2(a). On 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 $\phi_i$ of the electrical signal for different electrical phase-shifts at the reception stage. The expression of both measurement parameters can be seen in Eq. (7) and Eq. (9), respectively.

Considering the aforementioned definition of $R_i$, this parameter can be expressed as:

$$R_i = \frac{V_o(f, \Omega_1)}{V_o(f, \Omega_2)} = \frac{M(f, \Omega_1)}{M(f, \Omega_2)} = \frac{[1 + \left(\frac{2\beta}{1 + \beta^2}\right) \cos \Omega_1]^{1/2}}{[1 + \left(\frac{2\beta}{1 + \beta^2}\right) \cos \Omega_2]^{1/2}}$$  \hspace{1cm} (7)

where

$$M(f, \Omega_1, \Omega_2) = \alpha \left(1 + 2\beta \cos \Omega_1 \cos \beta \right)^{1/2}$$  \hspace{1cm} (8)

From (8), the expression of the magnitude corresponding to sensor $i$ at angular frequencies $\Omega_1, \Omega_2$ can be written as a function of $\Omega_2 = \Omega_2 - \Omega_1$.

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

$$\phi_i = \arctan \left[ \frac{-(\sin \Omega_1 + \beta_i \sin \Omega_2)}{\cos \Omega_1 + \beta_i \cos \Omega_2} \right]$$  \hspace{1cm} (9)

For a fixed value of the modulation frequency and the electrical shifts, both measurement parameters, $R_i$ and $\phi_i$, of the remote sensing point $i$ depend only on $\beta_i$ which is insensitive to external power fluctuations (see Eq. (3)) that might take place in the optical link between the sensing point and the transmission stage, thus performing a self-reference parameter. Moreover, both self-referencing parameters can be determined for any pair of values of angular frequencies ($\Omega_1, \Omega_2$) providing flexibility to the measurement technique at the remote sensing network for any desired operation point. Figure 4(a) and Fig. 4(b) show the theoretical curves for the $R_i$ parameter and the output phase $\phi_i$, respectively.
Let \( m(\phi_i) \) be the slope of the output phase response versus \( \beta \). From the theoretical curves shown in Fig. 4 the performance of both parameters can be resumed as:

- \( R_i > 1 \) and \( m(\phi_i) > 0 \) when \( \Omega_i - \Omega_2 > 0 \).
- \( R_i < 1 \) and \( m(\phi_i) < 0 \) when \( \Omega_i - \Omega_2 < 0 \).

3. Measurements and comparison study of both configurations

3.1 Experimental set-up

The electro-optical network configuration shown in Fig. 2(a) has been implemented using single-mode fiber in order to experimentally validate both self-referencing parameters simultaneously for two remote sensor channels. An erbium-doped broadband light source modulated at \( f = 10 \text{kHz} \) by an acousto-optic modulator was employed to launch optical power into the configuration through the broadband circulator. A pair of low-cost FBGs was used for each remote sensing point including their complementary ones (same central wavelengths) at the reception stage. Their central wavelengths were \( \lambda_{c1} = 1530.1 \text{nm} \), \( \lambda_{c2} = 1535 \text{nm} \) for FOSe and \( \lambda_{c1} = 1550.3 \text{nm} \), \( \lambda_{c2} = 1552.1 \text{nm} \) for FOSe 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 \( H_i \) and \( H_2 \), respectively, see Figs. 5(a) and 5(b). The tapers were obtained by elongation of single-mode fibre using a semi-automatic fabrication process. Once the tapers are fixed onto a micro-positioning system, the optical loss transmission coefficients of the tapers are sensitive to the displacement between the two fibre ends. Due to the tolerance of the elongation and positioning semi-automatic processes for obtaining the fiber sensors, there is a difference between sensors sensitivity to mechanical displacement.

The reflected signals were demultiplexed by a CWDM demux, collected by InGaAs photodetectors and phase-shifted by the electronic delay filters at the reception stage. A lock-in amplifier was used in this stage in order to obtain both self-referencing parameters \( R_i \) and \( \phi_i \), \( i = 1, 2 \).

Figure 5 shows the calibration curves of sensor loss modulation \( H_i \), \( i = 1, 2 \) for both sensors versus displacement. In order to test the hysteresis of the sensors, two sets of data were recorded by increasing and decreasing the input displacement. The resultant curves show a good agreement between the sensors, indicating a symmetric hysteresis behavior.
measurements, marked as fwd (forward) and bkw (backward), were taken for increasing and decreasing values of the displacement, respectively.

3.2 Self-reference test

The self-reference property of both measurement parameters was tested with regards to power fluctuations of the optical source. A single-mode variable optical attenuator (VOA) was located at different points in the transmission stage thus emulating unexpected power losses along the optical link from the optical source to the remote sensing point, up to 12dB.

Figure 6(a) and Fig. 6(b) show, respectively that there was no correlation between the measurements of both self-referencing parameters ($R_i$ and $\phi_i$) and the induced power attenuation with the VOA thus providing the self-reference property to the remote sensor network.

![Calibration curves and hysteresis of the sensor loss modulations](image)

Fig. 5. Calibration curves and hysteresis of the sensor loss modulations $H_1$ (a) and $H_2$ (b) for the taper based displacement sensors.

![Self-reference test](image)

Fig. 6. (a) Self-reference test of $R_i$ versus power fluctuations up to 12dB for different values of $\beta_i$ and $\beta_i = 0.25$. (b) Self-reference test of $\phi_i$ versus power fluctuations up to 12dB for different values of $\beta_i$ and $\beta_i = 0.25$.
3.3 Crosstalk analysis

In order to test the crosstalk between two sensors operating in adjacent CWDM channels, several measurements of the self-referencing parameters $R_i$ and $\phi_i$ (FOS$_i$) have been taken for different values of the sensor losses modulation $\beta_i$ (FOS$_j$) as shown in Fig. 7(a) and Fig. 7(b), respectively. Similar results were obtained when monitoring $R_j$ and $\phi_j$ (FOS$_j$) when $\beta_i$ (FOS$_i$) was changed. In both cases no crosstalk is induced due to changes in the sensor loss modulation of one sensor to the other, so both sensors can be interrogated simultaneously without mutual interference.

Fig. 7. Measurements of the $R$ parameter (a) and the output phase $\phi_j$ (b) versus $\beta_i$ (FOS$_i$) for different values of $\beta_j$ (FOS$_j$).

3.4 Sensitivity analysis

This subsection will be divided into two concerning each self-referencing parameter as the same analysis lead to different performances depending on the measurement parameter considered.

As the performance of both sensor channels (those including FOS$_1$ and FOS$_2$, respectively) is exactly the same for both self-referencing parameters from now on it is used a generic parameter $R$ or $\phi$, no matter the remote sensing point is being considered.

As defined in Section 2, $\Omega = \Omega_2 - \Omega_1$ being the difference between both phase-shifts (related to the sensor which is being interrogated) selected at the reception stage.

3.4.1 $R$ parameter

The sensitivity of the system $S_R$ to sensor losses (by means of $\beta$), defined as the partial derivative of $R$ with respect to $\beta$, $S_R = \frac{\partial R}{\partial \beta}$, is given by:

$$S_R(\Omega_1, \Omega_2, \beta) = \frac{(\cos \Omega_2 - \cos \Omega_1)[1 - \beta^2]}{(1 + 2\beta \cos \Omega_1 + \beta^2)^{3/2}(1 + 2\beta \cos \Omega_2 + \beta^2)^{3/2}}$$ (10)

From (10), $S_R$ depends on the phase-shifts ($\Omega_1$, $\Omega_2$) selected at the reception stage and not on the signal absolute phase or power, apart from $\beta$. 

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Figure 8(a) shows both measurements and theoretical curves (dashed lines) of the sensitivity of the $R$ parameter versus sensor losses, $\beta$, for different values of $\Omega$ and $\Omega_2$ when $\Omega > 0$. Notice that when $\Omega = 90^\circ$ and $\Omega_2 = 180^\circ$ a performance of $S_R \approx \left| I \right|$ can be obtained in the whole range of $\beta$. Different measurements concerning $S_R$ versus $\beta$ when $\Omega < 0$ have been tested showing good agreement with theoretical predictions as can be seen in Fig. 8(b). From this figure it is also shown that higher sensitivities can be obtained with $\Omega < 0$ at the reception stage.

Different calibration curves of the sensitivity of the $R$ parameter versus $\beta$ have been obtained for different phase-shift configurations at the reception stage. From the theory and measurements shown in this subsection the performance of $R$ with regards to the sensitivity showed the following results:

a) The sensitivity of the transfer function for a generic remote sensing point depends not only on the absolute difference of the phase-shifts related to that sensor selected at the reception stage but also on the pair of values selected in any case (see Fig. 8(a) and Fig. 8(b)).

b) The sensitivity response depends on the sign of $\Omega$ and higher sensitivities are obtained at $\Omega < 0$ for higher absolute values of $\Omega$ (see Fig. 8(b)).

c) For a fixed phase-shift difference $\Omega_i$, the highest sensitivity values are obtained when $\Omega_i = 180^\circ$ providing big variations in the whole range of $\beta \in [0,1]$.

d) Looking for high sensitivity and linearity self-reference technique in sensors with a measuring range from $\beta \in [0,1]; (\Omega_i, \Omega_2) = (90^\circ, 180^\circ)$ determines the best option for both phase-shifts at the reception stage.

![Figure 8](image-url)

Fig. 8. (a) $S_R$ versus $\beta$ for different values of the phase-shifts at the reception stage with $\Omega > 0$. (b) $S_R$ versus $\beta$ for different phase-shifts at the reception stage with $\Omega < 0$. In both cases dashed lines were obtained from the theory.

### 3.4.2 Output phase $\phi$ parameter

The sensitivity of the system $S_\phi$ to sensor losses (by means of $\beta$), defined as the partial derivative of $\phi$ with respect to $\beta$, $S_\phi = \frac{\partial \phi}{\partial \beta}$, can be expressed as follows:
\[ S_\phi(\Omega_1, \Omega_2, \beta) = \frac{\sin(\Omega_1 - \Omega_2)}{1 + 2\beta \cos(\Omega_1 - \Omega_2) + \beta^2} \quad (11) \]

From (11), \( S_\phi \) depends on the phase-shift difference between \( \Omega_1 \) and \( \Omega_2 \) selected at the reception stage and not on the signal absolute phase or power.

Figure 9(a) shows the theoretical curves of the absolute values of \( S_\phi \) versus sensor loss, \( \beta \), for different phase-shift difference values. As the performance of \( S_\phi \) is symmetrical with regards to \( \Omega = 90^\circ \), all the possible pair combinations of (\( \Omega_1, \Omega_2 \)) resulting with identical absolute value of \( \Omega \) will lead to similar results in terms of \( S_\phi \). Different measurements concerning \( S_\phi \) versus \( \beta \) have been tested showing good agreement with theory predictions as can be seen in Fig. 9(b).

Different calibration curves of the sensitivity of the output phase, \( S_\phi \), versus \( \beta \) have been obtained for different phase-shift configurations at the reception stage. From the theory and measurements shown in this subsection the performance of the output phase \( \phi \) with regards to the sensitivity showed the following results:

a) The sensitivity of the transfer function for a generic remote sensing point depends only on the absolute value of the phase-shifts difference (\( \Omega \)) related to that sensor selected at the reception stage and is independent from the sign of that phase-shift difference (see Fig. 9(a)).

b) Highest sensitivity values can be obtained at \( |\Omega| = 150^\circ \), providing big variations in the whole range of \( \beta \in [0,1] \). This fact can be seen in Fig. 9(b).

c) Taking into account the aim to obtain high sensitivities with no slope variations in the whole range of the sensor response, \( \Omega = |120^\circ| \) determines the best option to select both phase-shifts at the reception stage providing \( S_\phi \approx |\| \) in the whole range of \( \beta \).
3.5 Linear response

As the electro-optical topology proposed in this paper provides flexibility in terms of desired operation points of the network for each remote sensing point, in this section the linear response, which can be a desirable property when considering sensor performances, of both measurement parameters will be studied. It will also be provided phase-shift values at the reception in order to obtain the best performance in terms of linearity.

In the same way as the previous section (Section 3.4) the analysis of the linear response will be studied separately with regards to the self-referencing parameter considered, leading to different approaches.

3.5.1 $R$ parameter

Different theoretical curves of the $R$ parameter versus $\beta$ have been obtained for different phase-shift configurations at the reception stage. The performance of this measurement parameter was analyzed showing the following results:

a) The linear response of the $R$ parameter tends to be better when higher values of $\Omega_2$ at the reception stage are applied, independent of the values of $\Omega_1$ selected.

b) $(\Omega_1, \Omega_2) = (104^\circ, 180^\circ)$ provides the best performance in terms of linearity with a linear regression coefficient of $r = 0.9997$ in the whole $\beta$ range.

Figure 10 shows the measurements, theoretical curve and linear fit of the $R$ parameter versus $\beta$ when $(\Omega_1, \Omega_2) = (104^\circ, 180^\circ)$ is applied at the reception stage. The coefficient of linear adjustment to the experimental points was found to be $r = 0.9992$, close to the unit and to the theoretical value predicted by the model.

![Figure 10. Measurement of $R$ versus $\beta$ when $(\Omega_1, \Omega_2) = (104^\circ, 180^\circ)$ is applied at the reception stage (linear regression in solid line and theoretical curve in dashed line).]

3.5.2 Output phase $\phi$ parameter

Taking into account the output phase $\phi$ versus $\beta$, the performance of this measurement parameter shows the following results:

...
a) The best response in terms of linearity is provided by those phase-shift configurations at the reception stage when $\Omega = |120^\circ|$ is applied, with a linear coefficient of $r = 0.9993$ in the whole $\beta$ range.

b) Consequently, the best linear response is obtained when $\phi|_{\beta=0} = \alpha$ and $\phi|_{\beta=1} = \alpha \pm 60^\circ$. This means that maximum linearity is obtained when the output phase response varies $\Delta \phi = 60^\circ$ from $\beta = 0$ to $\beta = 1$.

Figure 11 shows the measurements, theoretical curve and linear fit of the output phase $\phi$ versus $\beta$ when $(\Omega_1, \Omega_2) = (0^\circ, 120^\circ)$ is applied at the reception stage (linear regression in solid line and theoretical curve in dashed line).

3.6 Resolution

In this section an estimation of the resolution of both measurement parameters of the network is presented. No uncertainty factors (such as thermal dependency or frequency-dependent noise) have been taken into account for this analysis.

Considering a generic function $f(x)$ it is truth that $\Delta f(x) = f'(x) \cdot \Delta x$. Analogously, if both parameters are considered as $f(x) = R(\beta)$ and $f(x) = \phi(\beta)$, the following relations, for any phase-shift configuration, can be obtained:

$$\Delta \beta_{\min} = \frac{\Delta \phi_{\min}}{S_{\phi}}$$  \hspace{1cm} (12)

and

$$\Delta \beta_{\min} = \frac{\Delta R_{\min}}{S_R}$$  \hspace{1cm} (13)
where \( S \) refers to the sensitivity of the parameter response considered and \( \Delta \beta_{\min} \), \( \Delta \phi_{\min} \) and \( \Delta R_{\min} \) are minimum deviations considered for the input \( \beta \) and the outputs \( R \) and \( \phi \), respectively.

Considering those minimum deviations as measurement uncertainties provided by the resolution of the Lock-in amplifier (\( \Delta \phi_{\min} = 0.05^\circ \); \( \Delta M_{\min} = 9 \times 10^{-5} \) V) but taking also into account the error propagation in the function \( f(x) = R(\beta) = M_1 / M_2 \) with respect of its two variables (considering separately the contribution due to both uncertainties), with \( M_1 = M(\beta) \) and \( M_2 = M(\beta) \), see Eq. (7).

It can be found that the parameter \( \Delta R_{\min} \) is given by:

\[
\Delta R_{\min} = \left( \frac{\Delta M_1}{M_1} + \frac{\Delta M_2}{M_2} \right) = \Delta M \cdot \left( \frac{1}{M_1} + \frac{1}{M_2} \right) \approx \frac{\Delta M}{M} \cdot 2
\]

with the approach \( M_1 \approx M_2 \) and where the term \( \Delta M \) corresponds to the Lock-in magnitude resolution (9x10^{-5} V) used in the measurements and \( M \) takes the value of 200mV (experimental value). That gives a value of \( \Delta R_{\min} = 9 \times 10^{-4} \) V.

Consequently, for both outputs it is possible to obtain the minimal input, \( \Delta \beta_{\min} \), required in the fiber-optic sensor from Eq. (12) and Eq. (13), respectively. The following Table estimates both parameters separately and comparatively at the same phase-shift configurations (see Table 1 footnote) at the reception stage for a \( \beta \) range from 0 to 0.5 with constant sensitivity:

| \( \Omega_1, \Omega_2 \) | \( R \) | \( \phi \) |
|----------------|----------------|----------------|
| \( (135^\circ,60^\circ) \) | 1.75 | -5.10^{-4} |
| \( (30^\circ,150^\circ) \) | 1.75 | -5.10^{-4} |
| \( (160^\circ,10^\circ) \) | 8 | -10^{-6} |
| \( (104^\circ,180^\circ) \) | 1 | -9.10^{-6} |

(a) arbitrary electrical phase-shifts
(b) best linearity condition for the output phase
(c) highest \( R \) sensitivity plotted in Fig. 8(b)
(d) best linearity condition for the \( R \) parameter

In all cases, with the approach of the \( R \) parameter (with the equipment used for the measurements) better resolutions can be obtained than measuring the output phase and, therefore, smaller increments of the sensor loss (\( \beta \)) could be detected. This is the reason why two electrical phase-shifts for each sensor providing flexibility in configuration at the reception stage can improve significantly the performance of the topology. In this analysis, differences in resolution between both parameters are also derived.

4. Conclusions

In this paper, a novel self-referenced radio-frequency FBG-based CWDM fiber-optic intensity sensor network with a reflective star topology for multiplexing and interrogation of \( N \) remote sensing points is proposed and analyzed following the Z-transform formalism. The RF modulation permits to avoid the effect of the flicker noise (1/f) at the reception stage. By including two delay lines at the reception stage implemented in the electrical domain instead of using a single electrical delay line, arbitrary modulation frequencies can be set and phase shift reconfiguration can overcome tolerance errors permitting an easy-reconfigurable
operation of the network. This means that any operation point for each remote sensor can be selected 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.

Two new self-referencing parameters have been defined for a generic remote sensing point of the network. They are $R_i$ which is defined as the ratio between voltage values at the reception stage for different electrical phase-shifts and $\phi_i$ which is defined as the output phase at the reception stage for different electrical phase-shifts. It was validated the self-reference property by simulating undesirable link losses up to 12dB. Also, it was demonstrated that no crosstalk is induced when two sensors operating in adjacent CWDM channels are simultaneously interrogated.

The performance of the network in terms of sensitivity, linear response and resolution was studied showing that both parameters allow a linear response of the topology. Furthermore, in terms of sensitivity and resolution, the parameter $R_i$ showed a better response than the output phase $\phi_i$, that means, higher sensitivities can be achieved and resolutions around two orders of magnitude below can be obtained considering $R_i$ as the self-referencing parameter of the network.

However, whereas the output phase parameter provides multiple choices of the phase-shifts at the reception stage leading to the same network performance, the parameter $R_i$ needs a more specific and controlled phase-shifts configuration at the reception stage in order to select an operation point for each remote sensing point. So depending on the specific characteristic of the sensor and the main target (as for example resolution or linearity in a greater range) one or another configuration will be selected.

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