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Interrogation of remote intensity-based fiber-optic sensors deploying delay lines in the virtual domain

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ABSTRACT

In this work a self-referencing intensity-based fiber-optic sensor using virtual instrumentation is presented. The use of virtual delay lines along with novel self-referencing techniques minimizing resolution and using a single frequency avoids all-optical or electrical-based delay lines approaches at reception. This solution preserves the self-referencing and performance characteristics of the proposed optical sensing topology, and leads to a more compact solution with higher flexibility for the multiple interrogation of remote sensing points. Results are presented for a displacement sensor demonstrating the concept feasibility.

Keywords: Optical sensing, passive remote sensing, self-referencing, digital filter, virtual delay line.

INTRODUCTION

Intensity fiber-optic sensors (FOS) provide an optical modulation signal as the measurement and use different self-referencing techniques to avoid noise errors from undesirable intensity fluctuations. They are easily integrated in wavelength-division multiplexing (WDM) networks, including those based on fiber Bragg gratings (FBGs), and can operate in reflective configuration [1, 2] for remotely addressing multiple sensing points with a single fiber lead [3, 4]. Configurations providing self-referencing techniques have been a motive of research during the last years. The use of all-optical resonant structures as basis of a self-referencing intensity type sensor has been widely identified in literature in an approach that is known as amplitude-phase conversion technique. Schemes based on Michelson [5], Sagnac [6], and ring resonators [7], with fiber delay coils [2, 8] are reported. Lately the long fiber coils are replaced with electrical filters at the reception stage of the remote sensor network [9]. This solution provides arbitrary modulation frequencies, compact sensing points and flexibility in the operation of the sensor network. Furthermore, a Coarse WDM (CWDM) reflective star sensor network topology for multiplexing and interrogation of N quasi-distributed self-referencing remote sensing points, using two electrical phase-shifts per sensor for flexibility purposes, has been recently studied [10]. Two measurement parameters were defined, one based on phase measurements and another based on amplitude measurements. This electro-optical self-referencing solution has been verified by modulating the light injected into the network and using a lock-in amplifier and electrical phase-shifters at the reception stage. On the other hand it has been recently reported a virtual delay line deployment [11], but in a Mach-Zehnder interferometric topology in which the optical source is modulated with two different frequencies and based on power-splitting topology rather than in a WDM approach. And the self-referencing parameter is defined as the ratio of voltage values of the optical output sinusoidal wave at a non-constructive and a constructive interference frequency, respectively.

In this work, the concept feasibility for the enhancement in the automation of the interrogation of remote fiber-optic intensity-based sensors deployed in the reflective WDM-based passive sensor network topology is presented. For testing the concept, the performance of an optical intensity sensor compatible with a CWDM network is analyzed, using a low-cost Analog-to-Digital converter (ADC) at the reception stage, and virtual instrumentation techniques supported on a LabVIEW® platform for developing two virtual delay lines and for controlling the sensor operation.

THEORETICAL BACKGROUND

The digital filter schematic for a single sensor electro-optical topology with two electrical delay lines is reported in [10], being H the sensor loss modulation. In the reception stage, electrical phase-shifts Ω_1 at the reference channel and Ω_2

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at the sensing channel are applied, respectively, to the RF modulating signal. The delay line filters are deployed in the electrical domain but with a coefficient β which depends on the optical sensor loss modulation H in the sensing point. Attending to the digital filter model of the sensor topology, the normalized system output, i.e. the transfer function of the system $H_0 = P_O / P_{in}$, can be directly identified with a digital Finite Impulse Response (FIR) filter in the Z-Transform domain. Two measurement parameters can be defined at the remote sensing point. On one hand the parameter R, which is defined as the ratio between the voltage values received, and on the other hand the output phase ϕ of the electrical signal, both for different electrical phase-shifts at the reception stage. Those parameters are given by:

$$R = \frac{V_O(f,\Omega_2)\big|_{\Omega_1=0}}{V_O(f,\Omega_1)\big|_{\Omega_2=0}} = \frac{[1+(\frac{2\beta}{1+\beta^2})\cos\Omega_2]^{1/2}}{[1+(\frac{2\beta}{1+\beta^2})\cos\Omega_1]^{1/2}} \quad , \quad \phi = \arctan\left[\frac{-(\sin\Omega_1 + \beta\sin\Omega_2)}{(\cos\Omega_1 + \beta\cos\Omega_2)}\right]; \text{with } \beta = \frac{m_S.R(\lambda_S).d_S}{m_R.R(\lambda_R).d_R} H^2 \qquad (1)$$

where m_R, $R(\lambda_R)$ and d_R are the RF modulation index, the reflectivity of the FBG and the photodetector response at the reference wavelength λ_R, respectively, and m_S, $R(\lambda_S)$ and d_S are those parameters but for the sensing wavelength λ_S. For a fixed value of the modulation frequency and the electrical shifts, both measurement parameters of a generic remote sensing point depend only on β which is insensitive to external power fluctuations in the optical link. Moreover, both self-referencing parameters can be determined for any pair of values of angular frequencies (Ω_1, Ω_2).

EXPERIMENTAL SETUP AND RESULTS

The experimental setup is shown in Fig. 1, where topology is performed partially in the optical domain and partially in the digital electronics domain.

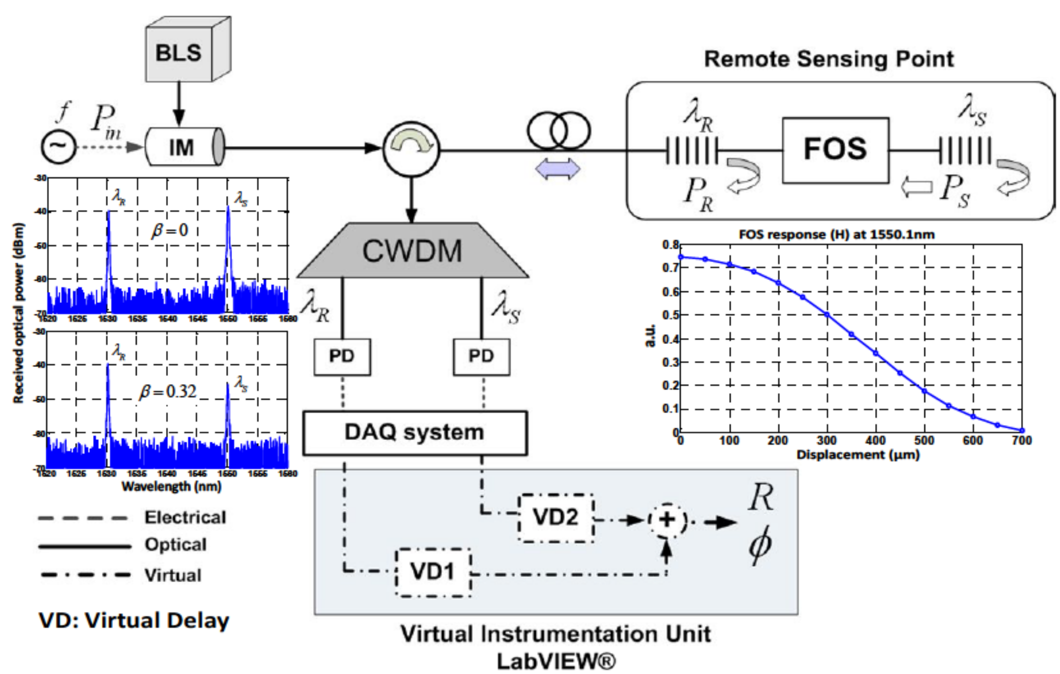

Figure 1. Experimental setup. Inset: calibration curve of the displacement sensor; and reference (λ_R) and sensing (λ_S) channels after sliced through the CWDM demultiplexer. BLS: Broadband Light Source, IM: Intensity Modulator, PD: Photodetector.

A broadband light source (BLS) modulated at a single frequency f=100Hz by means of an acousto-optic modulator is employed to launch optical power into the configuration through the broadband circulator. A pair of low-cost FBGs is used at the remote sensing point, being placed before and after the FOS, thus performing a Michelson interferometric scheme. Their central wavelengths are $\lambda_R = 1530.2\text{nm}$ and $\lambda_R = 1550.1\text{nm}$, compatible with standard ITU G.694.2 for CWDM networks. To test the concept, a SMF-based taper operating as a micro-displacement sensor is placed between each FBG with sensor loss modulation H. See Fig. 2-inset for its calibration curve. The optical signal is demultiplexed by a CWDM device and delivered to two different switchable gain InGaAs photodetectors. An analog/digital converter (DAQ – Data Acquisition) with the signal aggregation and delay line functionality achieved with virtual instrumentation techniques is located at the reception stage. This device performs a 14-bit Analog-to-Digital converter for each analog input and 48kS/s of maximum aggregate sampling rate. Finally a PC with LabVIEW® software is used to control the system. In the reception stage, each signal is compound by 240 samples as a compromise between performance/limitation of the DAQ. The displacement sensing system resolution is found to be 14μm when measuring the output phase, and 2.1μm when considering the parameter R. Both measurand resolution values are higher than those reported in [11], due to the reflective operation of the sensing structure. Nevertheless, since the number of samples and the total sampling time provided by the DAQ is the same, for a lower modulation frequency a better measurand resolution is expected. Nevertheless, if a greater resolution is required, a DAQ with higher sampling rate should be used.

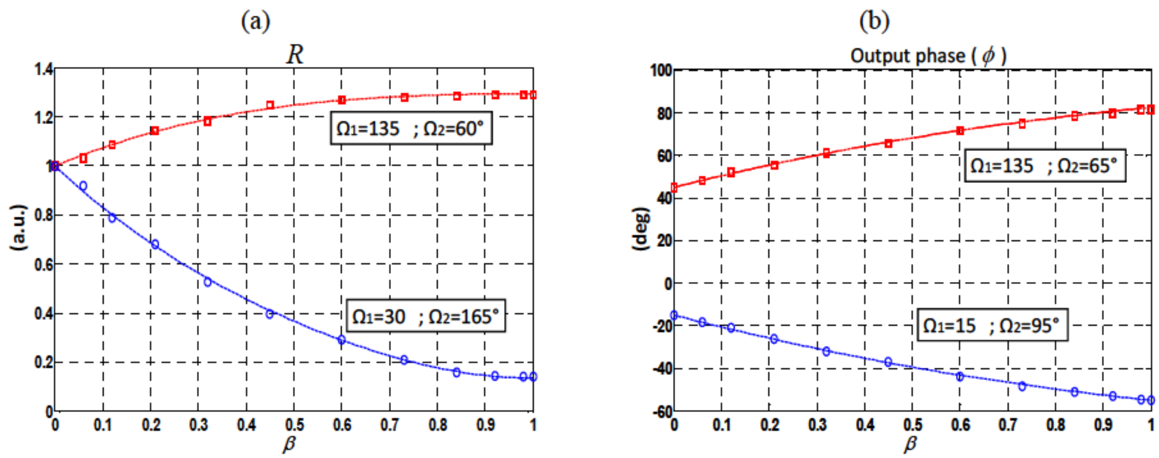

Figure 2. Experimental results and theoretical curves for both self-referencing parameters at different virtual phase-shifts, (a) R parameter; (b) Output phase ϕ. Theoretical curves are drawn in solid lines.

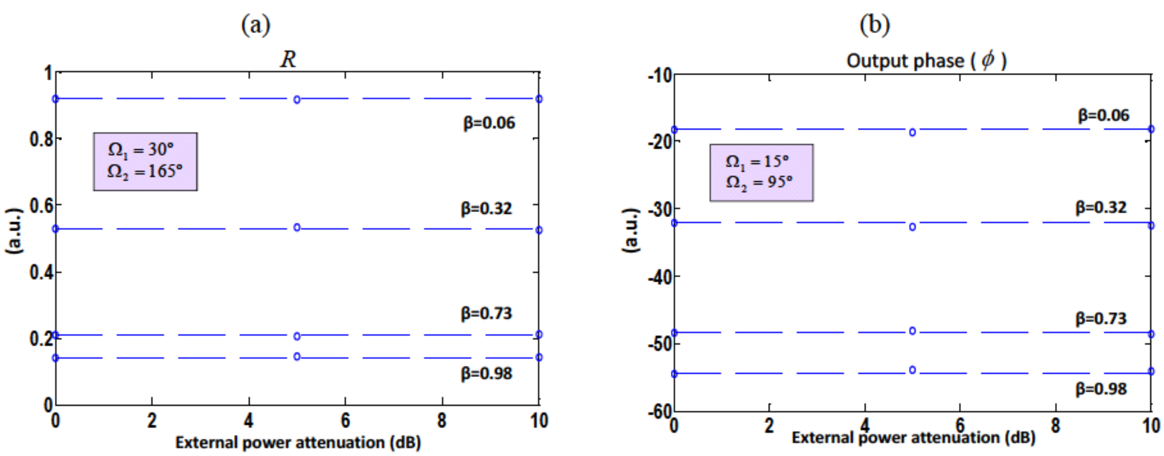

Figure 3. Self-reference test versus induced power losses (up to 10dB) for different values of β, for both measurement parameters.

Different calibration curves versus optical loss modulation of the sensor, β, are obtained, with different phase-shifting values. Results showed good agreement between theory and measurements, as can be seen in Fig. 2. In addition, the self-reference property of both measurement parameters is tested. A single mode variable optical attenuator (VOA) is located after the broadband circulator thus emulating unexpected power losses, up to 10dB, in the fiber lead from the optical source to the remote sensing point. At Fig. 3 is shown no correlation between the measurements of both self-referencing parameters and the induced power attenuation, as expected.

CONCLUSIONS

In this work a single radio-frequency self-referenced CWDM intensity-based fiber-optic sensor using virtual delay lines at the reception stage is presented. This topology takes advantage of the use of FBGs and CWDM devices, and has been demonstrated to provide an effective and compact strategy to operate in reflective configuration for exploiting fiber links. It also allows a high scalability and an enhancement of the power budget as CWDM devices with low insertion losses are used for spectral splitting. The proposed configuration avoids the deployment of physical delay lines, thus allowing an even more compact, cost-effective and easy-reconfigurable solution, through two delays, for sensor operation while keeping all the advantages of optical sensing. For testing the concept, a micro-displacement sensor is used, and two different self-referencing parameters have been tested. This solution can lead to a higher automation in the interrogation of future WDM-based remote sensor networks.

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