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Fiber optic intensity sensor referenced with a virtual delay line

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ABSTRACT

In this work a self-referencing fiber optic intensity sensor using virtual instrumentation is presented. To ensure higher flexibility and dynamic optimization, the use of an optical fiber delay line or an electrical delay line is avoided by implementing a delay line in the virtual domain, preserving the self-referencing and sensitivity characteristics of the proposed optical intensity sensing structure. Results are presented where displacement is measured with an 18 μm resolution demonstrating the concept feasibility.

1. Introduction

Fiber optic sensors provide unique advantages, such as immunity to electromagnetic interference, they are chemically and biologically inert since the basic transduction material (silica) is resistant to most chemical and biological agents and its packaging can be physically small and lightweight. Taking the advantage of the intrinsic low optical attenuation of the optical fiber, it is possible to operate them over very long transmission lengths, so that the sensor can easily be placed kilometers away from the monitoring station and data can be reliably transmitted [1].

Intensity based optical fiber sensors can offer low cost and simple technologic solutions, ensuring a large range of applications. However, this type of sensors requires a self-referencing mechanism in order to discriminate changes in the intensity of light due to the measurement parameter from intensity changes caused by intensity variations of the optical source, or along the optical system [1,2]. To implement a self-referencing mechanism in an optical fiber intensity sensor, many different methods can be used, such as in space [3], in time [4], in wavelength [5] and in frequency [6,7]. In the method described as "Intensity Modulation" of reference [6], due to the frequency modulation of the optical source, the electrical phase modulation difference between the received optical signal and the source oscillator allows the possibility of a range measurement that is not affected by intensity variations of the optical source. On the other hand, in reference [7], two fixed different electrical modulation frequencies create two distinct phase differences at the end of the optical topology. In this case, the intensity sensor information results from dividing the optical intensity at those two frequencies, without the need of comparing the phase difference. The sensor is also immune to intensity variations of the optical source while avoiding the use of more complex phase tracking electronics. Recently, D. S. Montero et al. have presented a self-referenced intensity sensor based on frequency referencing method and using an electrical delay line instead of an optical one [8].

In this paper, we present a self-referenced fiber optic intensity sensor based on frequency referencing method, where the required optical or electrical delay line for the referencing method is avoided [7,8]. Instead, virtual instrumentation techniques supported on a LabVIEW® platform are used to implement a virtual delay line and to control all the sensor operation. This approach permits to enhance the versatility and portability of these systems, allowing a dynamic control of the fiber optic sensing parameters. To test the concept, displacement measurement using the deformation of a fiber taper is employed.

2. Theory

Fig. 1 shows a Mach–Zehnder topology, where a physical optical delay line is considered only for description of the sensing concept applied in this work.

When the signal that modulates the intensity of the optical source (in this case a LED) is swept in frequency, a well defined transfer function occurs, regardless of the input optical power value. Analyzing this transfer function, that appears due to the phase differences between the optical intensity modulated waves from the two arms of the Mach–Zehnder structure, reveals some significant features. For some frequencies the output shows a maximum (constructive interference frequencies − f_C), while for other frequencies the beat produces lower levels of optical power (non-constructive interference frequencies − f_{NC}). The shape of this transfer function is only affected

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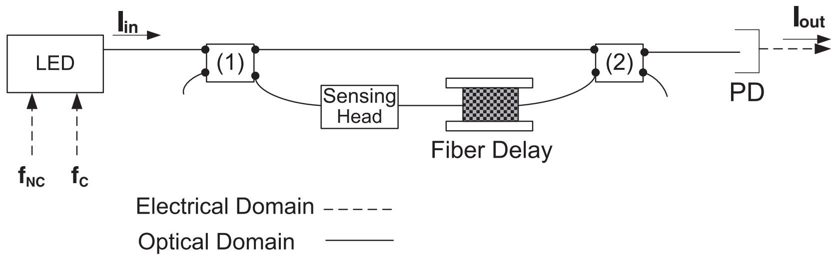

Fig. 1. Fiber optic intensity sensor referenced in frequency and based on a Mach–Zehnder topology.

by changes of the optical power within the Mach–Zehnder topology. Thus, by taking the ratio between the amplitude of two output waves associated with two referred modulation frequencies of the optical source, the result only depends on the losses that occur inside the Mach–Zehnder structure [1].

Analyzing the optical structure in Fig. 1, it is possible to obtain the amplitude of the output optical intensity modulation:

$$\frac{i_{out}}{i_{in}} = (1-\gamma)\left[(1-k) + kh(L)Ae^{-j\Omega_{dif}}\right] \tag{1}$$

where it is assumed that couplers 1 and 2 are identical and k represents their coupling coefficient, $(1-\gamma)$ is the coupling loss factor, $e^{-j\Omega_{dif}}$ is associated with the time delay of the propagation of the light in a fiber delay line of length L, h is the attenuation factor associated with the propagation of light in this fiber length, and Ω_{dif} is the electrical phase difference between the reference and the measurement optical signals, given by:

$$\Omega_{dif} = 2\pi\left(\frac{nL}{c}\right)f \tag{2}$$

In this relation, c is the vacuum speed of light, n is the optical fiber core refractive index, and f is the frequency of the sinewave modulation of the source optical power. Increasing or decreasing the length of the fiber delay line (L), or the modulation frequency (f), the electrical phase difference between the two interferometer arms can be properly adjusted. Therefore, the modulation of the input optical power with a specific amplitude but with different frequencies will originate an output signal with a variable amplitude.

This property can be explored to define a parameter that permits the determination of the measurand induced losses in the sensing head, independent of other optical power variations outside the Mach–Zehnder structure. This parameter, identified as *R parameter*, is defined as:

$$R \equiv \frac{V_{NC}}{V_C} \tag{3}$$

where V_{NC} and V_C are, respectively, the voltage values proportional to the optical output sinusoidal wave amplitude at a non-constructive interference frequency (f_{NC}) and at the constructive interference frequency (f_C).

3. Experimental setup and results

The experimental setup implemented in this work is presented in Fig. 2 (a), where the Mach–Zehnder configuration is performed partially in the optical domain and partially in the electric/digital domain using two photodetection/amplification blocks (PD1 and PD2) and an analog/digital converter (DAQ — Data Acquisition), with the signal aggregation and delay line functionality achieved with virtual instrumentation techniques.

Fig. 2 (b) presents the displacement sensing head implemented by a fiber taper. The device is fabricated by stretching a heated fiber, whose diameter is adiabatically reduced, forming a tapered structure that comprises a section with a gradual reduction in diameter, a narrow,

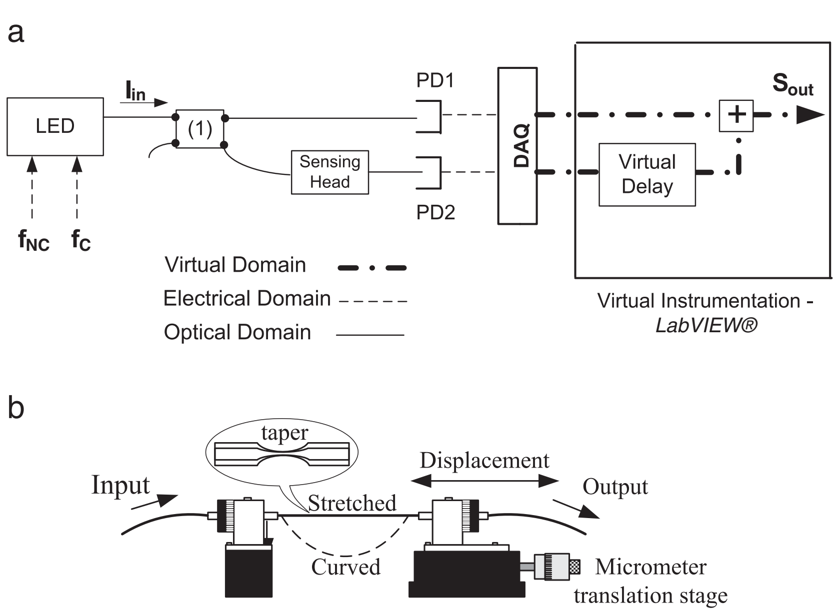

Fig. 2. (a) Experimental Setup, (b) detail of the displacement sensing head implemented by a fiber taper.

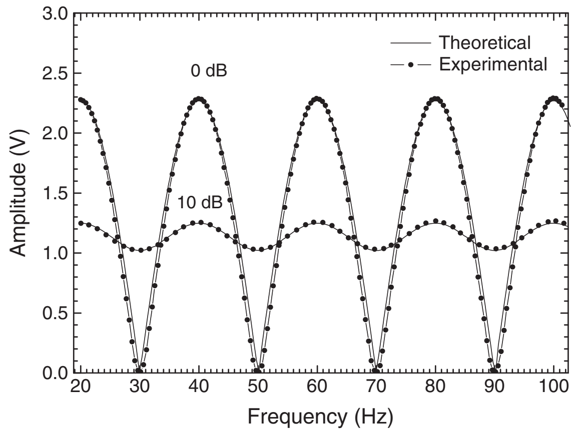

Fig. 3. Comparison between the theoretical and experimental transfer functions (amplitude of the output sinewave) for the cases of 0 dB and 10 dB of optical attenuation in the sensing branch.

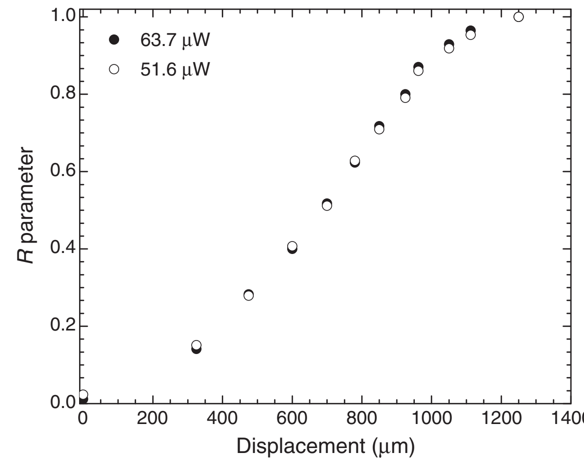

Fig. 5. Experimental results for the *R* parameter as function of displacement when the intensity of optical source is varied.

elongated filament called the taper-waist with uniform diameter followed by another tapered section where the diameter is gradually increased. In this particular case, the total fiber diameter was decreased adiabatically from 125 μm to around 50 μm [9]. Such structure is very sensitive to bending, increasing the optical loss as bending increases. Such behavior was used as the sensing mechanism.

As it can be seen, using a delay line in the virtual domain it is possible to avoid a physical optical or electrical delay line. With this setup, it is still possible to have the advantages of detecting the measure and optically, while having a more compact fiber optic sensor. The LED optical power is sinusoidally modulated with two different frequencies (f_{NC} and f_C) through modulation of its injection current, and the sensing head is modulated in intensity. The virtual instrumentation setup consists of a Data AcQuisiton Card (DAQ — model NI USB6211) and a PC with LabVIEW® software to control the system.

To observe the transfer function, an electrical signal applied to the hardware modulator is swept between 20 Hz and 100 Hz. In the reception stage, the signal acquired by the DAQ is compound by 500 samples. The delay was set to 25 ms. These two values resulted from a compromise between performance/limitation of the DAQ.

Fig. 3 shows the theoretical and experimental transfer functions for the cases of induced losses in the sensing head region of 0 dB and 10 dB, respectively. As it can be verified, for the two levels of attenuation, the experimental and theoretical results are globally in good agreement.

The intensity based displacement sensing head relied on a single-mode fiber taper. The arrangement, shown in Fig. 2 (b), was able to apply displacement via a micrometer translation stage, which in turn, induced curvature on the fiber taper and increased the fiber taper insertion loss. Therefore, a linear displacement could be converted into a curvature variation of the taper and, consequently, into an intensity modulation. When this sensing head was included in the set-up shown in Fig. 2 (a), a modulation of the *R* parameter with displacement occurs, with a dependence given in Fig. 4.

It can be observed that this dependence is non-linear, but with a relatively large quasi-linear region. To confirm the self-referencing mechanism, Fig. 5 shows the *R parameter* as function of displacement for two different optical power source values. The frequencies selected were $f_{NC}=30$ Hz and $f_C=40$ Hz, respectively.

In order to determine the sensing system resolution, two different displacements were introduced sequentially in the sensing head (0.88 mm and 1.06 mm, respectively). From the step amplitude variation and the *rms* output fluctuations during the periods of constant displacement it results a displacement resolution of 18 μm, as shown in Fig. 6.

Since the number of samples and the total sampling time for each measurement is the same, for lower f_{NC} and f_C frequencies a shorter number of sinusoidal periods can be used but with higher resolution and, therefore, a better measurand resolution is expected. Nevertheless, if a better measurand and resolution is required, a data acquisition board with higher sampling rate has to be used.

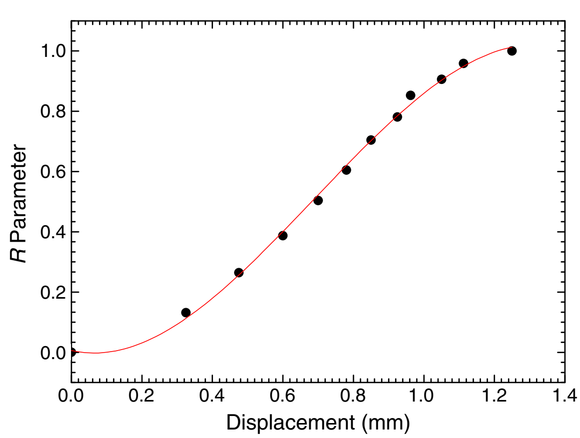

Fig. 4. Experimental results for the *R* parameter as function of displacement in the sensing head.

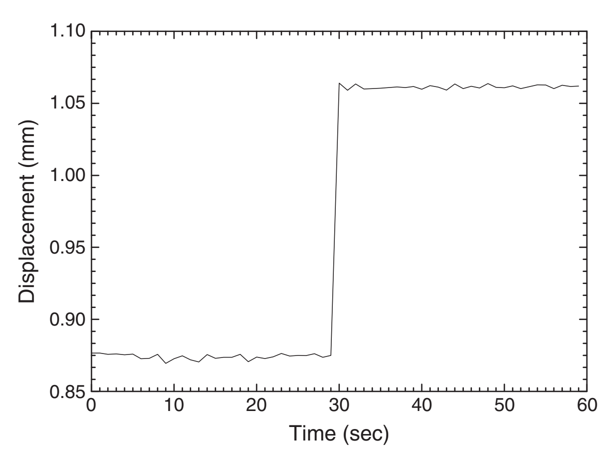

Fig. 6. Determination of the displacement resolution of the sensing head.

Due to the high flexibility of this approach, it is possible to use only one modulating frequency. In this case, for each measurement, the virtual delay is changed, producing the same result of having two modulating frequencies.

4. Conclusion

A self-referenced fiber optic intensity sensor using a delay line in the virtual domain has been demonstrated. This configuration allows a more compact fiber optic sensor, eliminating the necessity of using a physical, optical or electrical delay line, while keeping all the advantages of optical sensing. Moreover, it allows easy delay reconfiguration and optimization and, therefore, higher system flexibility. For testing the concept, displacement was measured with a resolution of 18 μm. The virtual instrumentation technique, here described, can be applied in different measuring applications, provided that the sensing head converts the parameter under observation into induced optical loss.

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