Self-referencing fibre-optic intensity strain sensors

J. Montalvo, P. C. Lallana, C. Vázquez

Electronics Technology Department, Carlos III University of Madrid
Avda. Universidad 30, 28911 Leganés, Madrid, Spain. Email: cvazquez@ing.uc3m.es

ABSTRACT

A theoretical and experimental study of a Radio-Frequency (RF) Ring Resonator (RR) configuration for self-referencing and improving the sensitivity of fibre-optic intensity sensors (FOS) is reported. An experimental set-up directly applying this scheme to a multimode (MM) fibre strain sensor is shown and discussed, and a generic calibration using a single-mode (SM) optical attenuator has also been reported in order to show the principle of operation and to validate the theoretical expressions. The separation between lead and transducer losses in the FOS is solved by converting light intensity fluctuations to be measured into ring resonator losses that produce high amplitude variations in the proximity of the RR resonance frequencies. Modulation of the optical carrier by a RF signal allows using cheap sources and simplifying the detection electronics.

Keywords: fibre-optic sensor, strain sensor, self-referencing, intensity-based sensor, ring resonator

1. INTRODUCTION

Fibre-optic sensors being electrically passive can remotely operate in the presence of strong electromagnetic interference, hostile environment, explosiveness. As strain sensors, resistive electrical gauges, which are not suitable for such kind of environment, have been considered for more than 30 years the most cost-effective strain sensors, exhibiting the best properties. In these cases, the detection circuit is based in the well-known Wheatstone bridge and they present hysteresis, drift and instabilities in essence. Etched fibres as strain gauges have been reported with better response as regards linearity and repeatability [1], with a response much less susceptible to temperature changes and other ambient instabilities than resistive gauges, because the thermal expansion coefficient of silica glass ($5 \times 10^{-7}/^{\circ}\text{C}$) is twenty times smaller than those of metals. There has been a lot of effort in developing fibre-optic intensity sensors, based on multimode (MM) and single mode (SM) fibres and specially on strain sensors [1-6]. These sensors use a simple but effective measuring process for detection and they need a self-referencing method to minimize the influences of long-term aging of source characteristics as well as short-term fluctuations of optical power loss in the leads to and from the transducer. Different time division and wavelength normalization self-referencing methods have been reported [2-3,7]. Other methods are based on the interfering concept, using an amplitude-phase conversion [8] or a frequency-based approach with Mach-Zehnder and Michelson topologies [9], and any of them are based on multimode fibres. More recently, the same concept has been used in a wavelength multiplexing configuration with SM fibres [10].

Ring resonators have a very sharp frequency response, which depends simultaneously on the ring losses and the coupling coefficient of the coupler. Even it can be controlled using optical amplifiers [11]. RR can act as filters of a RF frequency that modulates the optical carrier, using cheaper low coherence sources and simplifying the detection electronics.

In this paper, we propose a novel frequency-based approach to apply a self-referencing method in fibre-optic intensity strain sensors with an improved sensitivity. It relies on the ratio of the amplitudes of the RF signals corresponding to the interference in a RR at 2 different radio-frequencies. Its principle and properties will be discussed, and characterized using a SM commercial attenuator to simulate the behaviour of the FOS and a self-made MM strain sensor.

2. PRINCIPLE OF OPERATION

The new sensing scheme for self-referencing intensity based fibre-optic sensors, FOS, is shown in Fig. 1. It is a RR consisting of a variable optical coupler, K, ring losses, A, a FOS, and either optional optical amplification with remote pump lasing (G) or attenuation (ATN) could be used if necessary. The measurand modulates the RR loss and the RR power transfer function can be designed to be very sensitive to these variations, see an example in Fig. 2 for the measurements of P_3 in a RF spectrum analyzer, for a RR with a coupling ratio, $K=0.35$ and different loop losses H .

Fig. 1. General schematic of a RR for self-referencing fibre-optic intensity sensors.

By using this configuration, a reduction of the error contribution of light source fluctuations and short-term fluctuations of optical power loss in the leads to and from the transducer is achieved. In this frequency normalization method two frequencies are used, the sensor channel at frequency f_1 and the reference channel at frequency f_2 , see Fig. 2. This self-referencing technique does not affect the system dynamic range as other time-domain normalization techniques [1, 7].

Fig. 2. RF spectrum analyser measurements of the RR output power for different H values.

2.1. Ring resonator

A RR acts as a notch, an all-pass or a selective filter depending on the net gain, H , in the loop [9-10]. If we consider a RR with a FOS and optional amplification or attenuation within the ring, see Fig. 1, with the output power P_3 and the input power P_1 ; its relative output power, P_{r0} as a function of frequency, is given by:

$$P_{r0} = \left| \frac{P_3}{P_1} \right| = \left[(1-\gamma)^2 \frac{K^2 + [(1-2K) \cdot H]^2 + 2 \cdot K \cdot (1-2K) \cdot H \cdot \cos(\beta \cdot L)}{1 + (K \cdot H)^2 - 2 \cdot K \cdot H \cdot \cos(\beta \cdot L)} \right]^{1/2} \quad H = e^{-\alpha \cdot L} \cdot G \cdot A \cdot (1-\gamma) \cdot F(m) \quad (1)$$

where G is the power gain of the amplifier, A are the ring losses, m is the measurand, $F(m)$ is the FOS calibration curve, γ , K are the excess loss and coupling constant of the coupler, L is the loop length; β , α are the propagation constant and the attenuation coefficient of the waveguides. From Eq. (1) we see that the power transmission, P_3 goes to zero when:

$$\cos(\beta L) = -1, \text{ and } H = \frac{K}{1-2K} \quad (2)$$

The condition $\cos(\beta L) = -1$ determines that the minima of P_3 are located at the frequencies given by:

$$f_k = FSR \cdot (2k+1) \quad \text{with } k = 0, 1, 2, \dots \text{ and } FSR = \frac{c}{2 \cdot n_g L} \quad (3)$$

where c is the speed of light, f_k is the modulating frequency and n_g is the waveguide group index.

2.2. Operation point and sensitivity

The output power P_3 , at the reference channel, is chosen to be in the frequency of the maximum. In the proposed

frequency normalization method, the measurement parameter is the ratio $\frac{P_{r0}(\beta, L)}{P_{r0}|_{\cos(\beta L)=1}}$, named R_M .

The quiescent point is defined in the absence of the measurand, and ideally P_{r0} should be zero. Using Eq. (1) and Eq. (3), it is derived that this condition is fulfilled if the RR parameters K and H_0 are given by:

$$H_0 = \frac{K}{1-2 \cdot K} \quad \text{with } H_0 = (1-\gamma) \cdot e^{-\alpha L} G \cdot A \cdot F(m_0) \quad (4)$$

Fig. 3. Theoretical calibration surfaces, R_M (left: $K=0.1$, right: $K=0.2$). $L=1080$ m

As it can be seen in Fig. 3, the operation point depends on K and H_0 , so for any H_0 depending on the RR losses, there is an optimum K value for achieving a higher sensitivity. The normalized sensitivity is defined as:

$$S_M = \frac{P_{r0}(\cos \beta L = +1)}{P_{r0}(\beta, L)} \cdot \frac{\delta \left[\frac{P_{r0}(\beta, L)}{P_{r0}(\cos \beta L = +1)} \right]}{\delta H} \quad (5)$$

It has been analyzed its dependence as a function of H and using different frequencies to verify that the highest sensitivity is achieved for a RF sensor frequency close to the minimum condition ($\cos(\beta L) \rightarrow -1$).

3. MEASUREMENTS

The sensing scheme proposed is valid for any SM or MM intensity-encoded sensor. In this section, a generic calibration using a SM optical attenuator is reported to show the principle of operation and to validate the theoretical expressions.

The experimental set-up is made of a LD of $1.5 \mu\text{m}$, with 5MHz linewidth, that is internally modulated with a RF signal coming from the tracking generator of a RF spectrum analyzer (Tektronix 2714) as in [11]. The sensing scheme (see Fig. 1) is made of a polarization maintaining 2X2 variable ratio fibre coupler from Fibrepro with pigtails of 1m, 1Km of standard SM fibre (for avoiding the large coherence length of the laser, future experiments will be made with a worse LD), different patch cords and an attenuator simulating the FOS action. Mostly FC/APC connectors are used in the set-

up. The optical detection is carried out by an optical-to-electrical (OE) converter (Thorlabs D400FC). The sensor channel frequency f_1 is 1207 Mhz, and the reference channel frequency f_2 is 1302 Mhz. Measurements are shown in Fig. 4, showing a great agreement with theory.

In a second experiment, we have analysed the effect of including a 1 m MM G.651 fiber patch cord between two 1m SM fibers, all with ST connectors. Coupling losses were around 2dB at 1550nm. The response of a MM strain sensor has been simulated by peeling 20 cm of the jacket of the fiber patch cord and twisting it in 10 spirals around an elastic cylinder of 0.4cm diameter and we achieved a MM intensity-based strain sensor with 5 dB extinction ratio and nominal losses of 4dB. These values are under the margin of operation of the RR configuration.

Fig. 4. R_{M1} for $K=0.22$: Measurements (o), theory (—)

4. CONCLUSIONS

Self-reference fibre-optic intensity strain sensors are reported. They are based on the different intensity strain sensors previously reported by other authors embedded in a single mode ring resonator as the self-reference technique. Sensor sensitivity and design parameters are theoretically analysed. The proposed scheme is flexible because the point of operation is fixed by the coupling coefficient of a coupler and the quiescent ring losses and can be optionally controlled with optical gain. Calibration curves using an attenuator to simulate the effect of an intensity based sensor are measured to validate the principle of operation and the design equations. The ring resonator operates in incoherent regime and a cheaper low coherence source can be used. SM fibers are used in the lead to and from the transducer and the RR, but the strain sensor itself can be made of SM or MM fibers as most of the strain sensors reported up to date. Some measurements with a MM strain sensor are also reported showing the feasibility of the method for those types of sensors.

5. ACKNOWLEDGEMENTS

We wish to thank J. M. Sánchez Pena. This work was supported by CICYT (TIC2003-03783).

6. REFERENCES

1. Masoud Vaziri and Chin-Lin Chen, "Etched Fibers as Strain Gauges" *J. Light. Techn.*, vol 10, n° 6, pp. 836-841, 1992.
2. E. Udd, "Fiber Optic Smart Structures", John Wiley and Sons, New York, 1995
3. J. W. Berthold III "Historical Review of Microbend Fiber-Optic Sensors" *J. Light. Techn.* vol. 13, pp 1193-1199, 1995.
4. T. Abe, Y. Mitsunaga and H. Koga "A Strain Sensor Using Twisted Optical Fibers" *J. Light. Techn.* vol. 7, pp 525-529, 1989.
5. A. Martin et al "A novel optical fiber-based strain sensor" *IEEE Phot. Tech. Lett.*, vol. 9, pp. 982-984, 1997
6. A. Djordjevich, "Curvature gauge as torsional and axial load sensor", *Sensors and Actuators A* 64 (1998), pp. 219-224.
7. W. B. Spillman and J. R. Lord "Self-referencing Multiplexing Technique for Fiber-Optic Intensity Sensors" *J. Light. Techn.* vol. LT-5, pp 865-869, 1987.
8. P. Sixt, G. Kotrotsios, L. Falco and O. Parriaux "Passive Fiber Fabry-Perot Filter for Intensity-Modulated Sensors Referencing" *J. Light. Techn.* vol. LT-4, pp 926-932, 1986.
9. J. M. Baptista, J. L. Santos and A. S. Lage "Mach-Zehnder and Michelson topologies for self-referencing fiber optic intensity sensors", *Opt. Eng.* vol. 39, pp. 1636-1644, 2000.
10. J. M. Baptista, S. Abad, G. M. Rego, L. A. Ferreira, F. M. Araujo and J. L. Santos "Wavelength multiplexing of frequency-based self-referenced fiber optic intensity sensors", *Opt. Eng.* vol. 43, pp. 702-707, 2004
11. M. C. Vázquez, B. Vizoso, M. López-Amo, y M. A. Muriel "Single and double amplified recirculating optical delay lines as fiber-optic filters" *IEE Electronic. Letters*, vol. 28, pp. 1017-1019, 1992.