Curvature sensing using an added-signal in a fiber-optic cavity ring-down system

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ABSTRACT

This work presents a fiber-optic Cavity Ring-Down (CRD) configuration using an added-signal for curvature sensing. An Optical Time-Domain Reflectometer (OTDR) was used to send impulses down into the fiber loop cavity, inside of which a long period grating (LPG) was placed to act as sensing device. The added-signal was obtained by the sum of several conventional CRD impulses, thus providing an improvement on the curvature sensitivity when compared to the conventional CRD signal processing. Sensitivity to applied curvature of 15.3 μs/m^{-1} was obtained. This result was found to be 20-fold the one obtained for the conventional CRD signal processing.

Keywords: Cavity ring down, curvature, long period grating, OTDR, optical fiber sensors.

1. INTRODUCTION

(LPGs) are well-known fiber devices that have been used for a wide range of sensing applications [1]. In 1998, Lee et al. [2] reported the curvature sensitivity of a pair of in-series LPGs. It was shown that the interference fringes formed by the LPG pair were sensitive to the loss in the cladding mode, which could be induced by bending the fiber. Later, LPGs written in commercially available boron-codoped fibers were shown to exhibit high temperature and bending sensitivities [3]. A few years later, Frazão et al. [4] reported an alternative technique to interrogate an LPG: to read the amplitude changes with applied curvature, a conventional optical time domain reflectometer (OTDR) was used. Meanwhile, the same research group produced a Mach–Zehnder curvature sensor based on a Singlemode-multimode-singlemode (SMS) fiber layout, where the multimode interference phenomenon was combined with the operation of an LPG [5]. Wang et al. [6] demonstrated that the UV laser-induced LPG is independent of the bend-directions, while the bend-sensitivity of CO_2 laser-induced LPFGs is strongly dependent on the curved directions. Jin et al. [7] presented instead a directional bend sensor based on an LPG formed by introducing periodic grooves along one side of a photonic crystal fiber (PCF) with a focused CO_2 laser beam. Recently, LPGs have been fabricated in a side-hole fiber (SHF) by using a pulsed CO_2 laser [8]. In a different perspective, Wang et al. [9], proposed a fiber device based on overlapping an LPG on a fiber Bragg grating (FBG), which have shown to be capable of measuring directional bending and temperature.

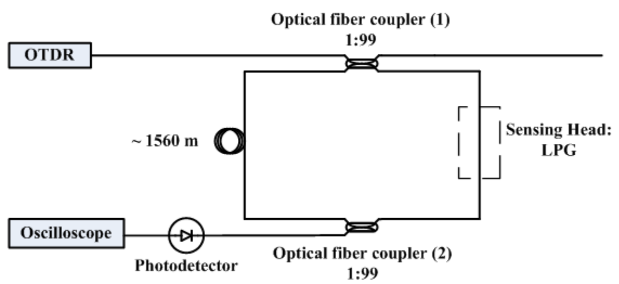
Cavity ring-down (CRD) spectroscopy is a well-established technique that gained popularity with the demonstration of highly sensitive direct absorption measurements with pulsed light sources [10].The combination of optical fibers and the CRD scheme has shown significant potential in fiber-optic sensing applications, namely, for the measurement of strain [11], pressure [12], temperature [13], refractive index [14] and biochemical sensing [15]. Lerber et al. [16] reported a CRD scheme that enabled measurements of optical losses in high-finesse fiber-optic cavities induced by fiber bending.

This work presents a fiber-optic ring down system that uses an OTDR as optical source modulated and an LPG inside the fiber loop as sensing device. The LPG was interrogated using (1) the CRD conventional signal processing and (2) when an added-signal was applied in the fiber loop. In the second case, the added-signal was obtained by the sum of several conventional CRD impulses. The LPG was submitted to curvature in these two distinct cases.

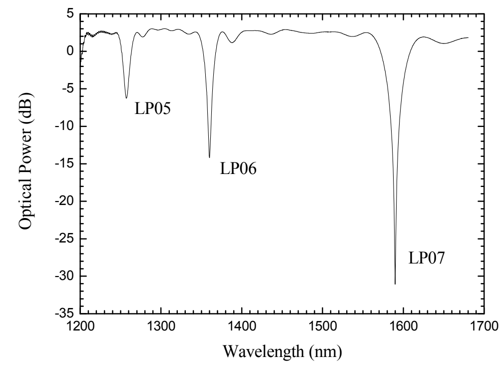
24th International Conference on Optical Fibre Sensors, edited by Hypolito José Kalinowski, José Luís Fabris, Wojtek J. Bock, Proc. of SPIE Vol. 9634, 96341G · © 2015 SPIE
CCC code: 0277-786X/15/$18 · doi: 10.1117/12.2194785

2. EXPERIMENTAL RESULTS

In this approach The cavity is composed of two standard 1:99 optical fiber couplers (2 × 1), a fiber loop with ~1560 m (SMF 28) and an LPG as sensing device. The LPG placed inside the fiber loop cavity was written by UV in SMF28e with a period of 335 nm and a length of 25 mm. A commercial OTDR (Yokogawa AQ7270) is used to send impulses down into the fiber cavity, instead of the usual laser and modulator setup [17]. The train of pulses is coupled via 1% arm of the input optical coupler, rings around inside the fiber loop and is coupled out via 1 % arm of the output coupler; the amplitude of the output pulses decay temporally due to the total existing losses in the fiber loop (fiber loss, fiber couplers insertion losses, LPG transmission attenuation), passes through a photodetector (gain of 50 dB) and is monitored in an oscilloscope. The output signal of the OTDR is used only as optical modulated source [18]. The advantage of using this equipment is to allow system optimization either in terms of impulse and optical power – allowing its use in long distance applications. Furthermore, the use of a multimode laser source increases the optical power inside the fiber loop [19]. The experimental setup of the proposed CRD system is shown in Figure 1a); the optical spectrum of the LPG obtained by an optical spectrum analyzer is shown in Figure 1b).



(a)



(b)

Figure 1. a) Experimental setup of the proposed CRD that uses an LPG as sensing head. The optical modulated source is an OTDR that launches the input signal inside the fiber cavity; the output signal is monitored by means of a photodetector and an oscilloscope. b) Optical spectrum of the LPG used as sensing head in the proposed CRD configuration.

Figure 3 shows the cavity ring-down trace for the two cases when the LPG was interrogated using (1) the CRD conventional signal processing and (2) when an added-signal was applied in the fiber loop. The LP_{07} resonance mode of the LPG is positioned at approximately 1590 nm and is situated in the slope of the OTDR multimode laser, which is centered at 1550 nm and has a bandwidth of 50 nm.

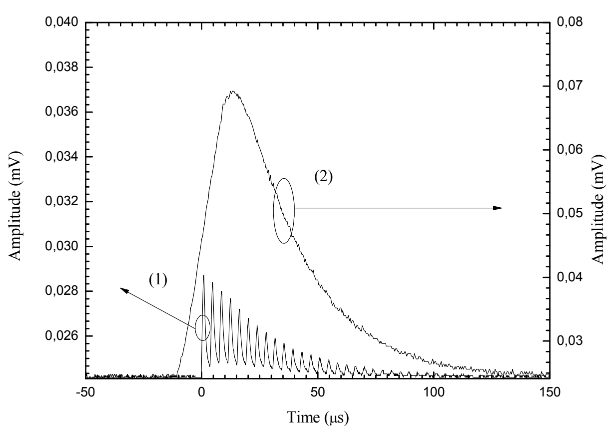


Figure 3. Cavity ring down trace for (1) conventional configuration and (2) added-signal obtained by the sum of several conventional CRD impulses.

In the first case (1), the OTDR sent impulses of 1 μs at 1550 nm down into the fiber cavity; the time of a single round trip is ca. 3.85 μs and is strongly dependent of the cavity length. An exponential fit was also performed and a ring-down time of 23.7 μs was attained. In the second case (2), the OTDR sent impulses of 20 μs at 1550 nm in order to obtain the added-signal. After performing an exponential fit, a ring-down time of 43.3 μs was obtained. Such results show that the added-signal increases the optical power but increases as well the ring-down time due to the sum of the several loops that light travels inside the ring.

The behavior of this structure as a curvature sensor was duly characterized. The fiber was fixed at two points, at a distance of 250 mm from each other; one of these points is a translation stage that allows the fiber to bend. The bending displacement, d, was applied to the LPG via sequential 100 μm displacements. Hence, the curvature ($1/R$) of the fiber structure changed by $2d/(d^2 + L^2)$, where L is half the distance between the two fixed points. Curvature was then applied to the LPG in the two distinct situations presented previously. The results for the added-signal configuration are depicted in Figure 4 (a). The amplitude of the added-signal decreases with increasing curvature, as result of bending the LPG. The proposed CRD configuration uses the LPG response in terms of intensity variation instead of the usual wavelength change with applied curvature. Therefore, the advantage in this case is the elimination of cross-sensitivity to temperature [4]. The ring-down time as a function of curvature was also determined for both conventional CRD- and added-signals, as depicted in Figure 4 (b). Results show that the sensitivities obtained for the added-signal and conventional CRD signal are 15.3 μs/m^{-1} and 0.74 μs/m^{-1}, respectively. The added-signal configuration presents a sensitivity 20-fold the one obtained for the conventional CRD signal processing.

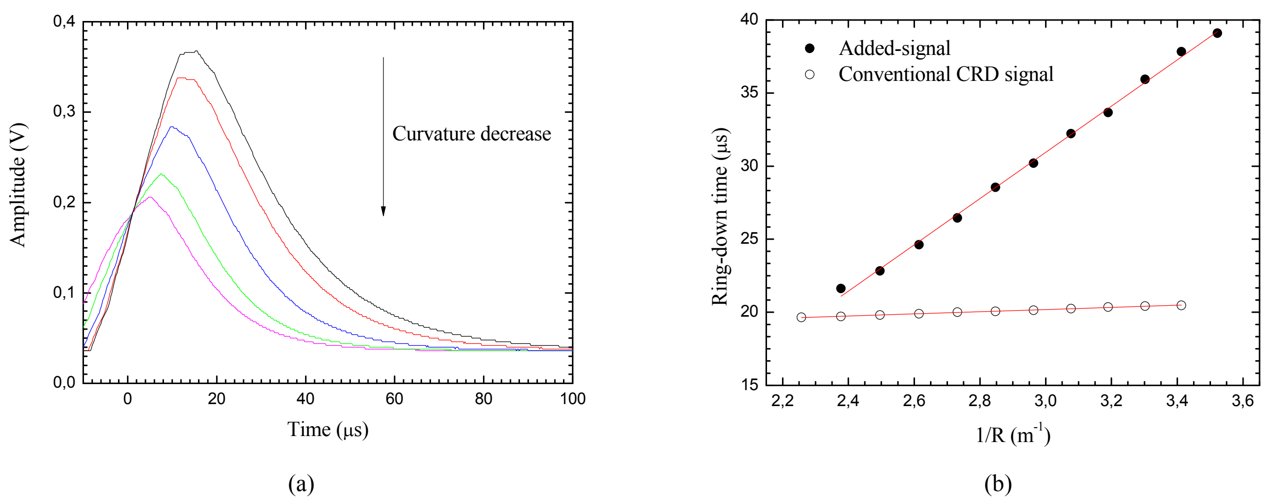


Figure 4. (a) Cavity ring-down trace obtained when an added-signal is applied in the fiber loop and its behavior when curvature is applied to the LPG. (b) Ring-down time versus curvature applied to the LPG when interrogated by the conventional CRD signal processing and added-signal.

3. CONCLUSIONS

In conclusion, an optical fiber CRD configuration was proposed, making use of an added-signal for curvature sensing. An OTDR was used to send impulses down into the fiber loop cavity, inside of which an LPG was placed to act as sensing device. The added-signal was obtained by the sum of several conventional CRD impulses, which provided an improvement on the curvature sensitivity when compared to the conventional CRD signal processing. Curvature was applied to the LPG in the range of 2.2 to 3.6 m^{-1} and a sensitivity of 15.3 μs/m^{-1} was obtained for the added-signal processing. This values was found to be 20-fold the one obtained for the conventional CRD signal processing (0.74 μs/m^{-1}). Since the LPG is interrogated in terms of intensity variations, it is possible to eliminate the common problem of cross-sensitivity to temperature. Also, the CRD system is a low-cost configuration when compared to the usual interrogation technique using an optical spectrum analyzer.

ACKNOWLEDGMENTS

This work was financed by the FCT, Fundação para a Ciência e Tecnologia (Portuguese Foundation for Science and Technology) and by the ERDF (European Regional Development Fund) through COMPETE Programme (Operational Programme for Competitiveness) within project FCOMP-01-0124-FEDER-037281. S.S. received a Pos-Doc fellowship (ref. SFRH/BPD/92418/2013) also funded by the EU and the Portuguese State. The FCT-DST (India) funding under Indo-Portuguese research cooperation in science & technology is also acknowledged.

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