Refractive index sensing using a multimode interference-based fiber sensor in a cavity ring-down system

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ABSTRACT

This work presents a multimode interference-based fiber sensor in a cavity ring-down system for sensing temperature-induced refractive index (RI) changes of water. The sensing head is based in multimodal interference (MMI) and it was placed inside the fiber loop cavity of the CRD system. A modulated laser source was used to send pulses down into the fiber loop cavity and an erbium-doped fiber amplifier (EDFA) was placed in the fiber ring to provide an observable signal with a reasonable decay time. The behavior of the sensing head to temperature was studied due to its intrinsic sensitivity to said parameter – a sensitivity of -1.6×10^{-9} μs/°C was attained. This allowed eliminating the temperature component from RI measurement of water and a linear sensitivity of 580 μs/RIU in the RI range of 1.324-1.331 was obtained.

Keywords: Cavity ring down, refractive index, multimode interference, optical fiber sensors.

1. INTRODUCTION

Cavity ring-down (CRD) spectroscopy is a well-established technique that has been target of research in the spectroscopy field, specially by the demonstration of highly sensitive direct absorption measurements with pulsed light sources [1].The implementation of optical fibers led to new fiber optic-based CRD systems which, in turn, used a fiber loop operating as the resonant cavity. This configuration quickly obtained popularity in the scientific community, mainly for presenting an effective alternative to the usual CRD configuration [2]. In the last decade, the CRD technique has been devoted to sensing applications [3]. Many efforts have been made in developing optical fiber sensors suitable for measuring refractive index (RI), when integrated in a CRD configuration. The challenge of this task is to obtain a fiber structure sensitive to the external medium, enough to originate amplitude variation of the optical spectrum and, consequently, inducing losses on the CRD output signal. In early reports, the Long Period Grating (LPG) was found to be a suitable solution for RI sensing in a CRD configuration [4]. The LPG was placed inside the fiber ring and studied the ring-down decay time of the fiber loop as a function of the RI variation of the external medium. Results indicated an amplitude signal decay of -7.16 dB in the RI range of 1.35–1.43. Later, a tilted fiber Bragg grating was proposed as sensing element inside the fiber loop [5]; using this configuration, a maximum sensitivity of 154 μs/RIU in the high RI range was obtained. Also, a micrometric channel was inscribed in the fiber of the cavity ring by means of femtosecond technique [6]. This configuration allowed measuring gels with different RIs and a sensitivity up to 300 μs/RIU close to the RI of 1.452 was obtained. A partially etched cladding singlemode fiber was used as sensing element inside the fiber ring [7]. A maximum detection limit for an RI change of 3.2×10^{-5} was demonstrated in the RI range of 1.3388–1.3398. Recently, a Mach–Zehnder interferometer based on a Photonic Crystal Fiber was integrated in the cavity ring for the detection of RIs in liquid medium [8]. This configuration presented a linear sensitivity of 11.7 $\mu s^{-1} RIU^{-1}$ with a corresponding minimum detectable of 7.8×10^{-5} RIU.

This work presents a CRD system that uses an MMI-based fiber device inside the fiber loop for measuring RI. The sensing head is based on multimodal interference, and relies on a singlemode – coreless-multimode – singlemode fiber configuration. Usually, the MMI structure presents high losses and, in order to compensate them, an EDFA was inserted in the loop cavity. The sensing device was submitted to RI changes of water caused by temperature variation.

2. EXPERIMENTAL RESULTS

In this approach, the CRD system is composed by a modulated laser source, two standard 1:99 optical fiber couplers (2×1), a fiber loop with ~1 km (SMF 28), an EDFA, a photodetector, and an oscilloscope. Inside the fiber loop was placed the MMI-based fiber device for sensing purposes. The experimental setup of the proposed CRD configuration is shown in Figure 1 and, on the right side, the optical spectrum of the MMI-based fiber sensor obtained with an optical spectrum analyzer.

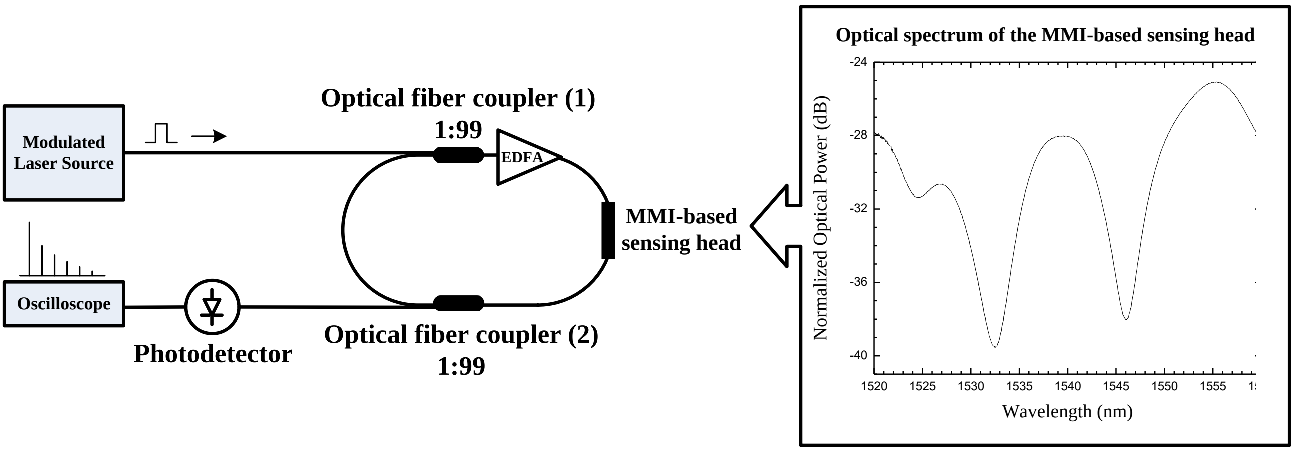


Figure 1. Experimental setup of the proposed CRD configuration that uses an MMI-based fiber structure as sensing head. On the right side, optical spectrum of the MMI obtained with an optical spectrum analyzer.

The modulated laser source is used to send pulses (500 ms @ 1550 nm) down into the fiber loop – 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 decays with time due to the total existing losses in the fiber loop (fiber loss, fiber couplers insertion losses, MMI transmission attenuation), passes through a photodetector (gain of 40 dB), and is monitored in an oscilloscope. The EDFA was made in the lab, has 2 m of an erbium-doped fiber (losses of 14 dB/m @ 980 nm) and it was inserted in the fiber loop for signal amplification of the CRD configuration.

The sensing head is based on multimodal interference and relies on a singlemode – coreless-multimode – singlemode fibre configuration (SMF – coreless-MMF – SMF). The coreless-MMF is a pure silica fiber with 125 μm-diameter and 20 mm-length, which was spliced between two SMFs and interrogated in transmission (see Figure 1b). The principle of this fiber structure underlies on the concept that when the light field coming from the input SMF enters the coreless-MMF, interference between the different modes occurs along the MMF section. The light is coupled into the output SMF – and it will depend on the amplitudes and relative phases of the several modes at the exit end of the coreless-MMF. Therefore, the coupling efficiency, for a given length of the MMF section, is strongly wavelength-dependent. In this work, the operating mechanism of the sensing head relies on destructive interference at the output end of the coreless-MMF section, which occurs for a specific length of the MMF used (20 mm). The result is a band-rejection filter in the operation wavelength range of 1520–1560 nm (see Figure 1b). It is expected that the MMI-based fiber sensor head is sensitive to the external medium, namely to RI trough wavelength variation [9]. Thus, the wavelength variation is due to the effective index variation of the guided modes of the coreless fiber-MMF when subjected to RI changes of the external medium. This behavior of the sensing head comes with a variation of the signal amplitude as a consequence of the change in reflection coefficient at the multimode fiber-to-liquid interface. The signal amplitude decreases with increasing RI of the external medium as it approaches the silica RI (coreless-MMF). Thus, the sensing head developed in this work is able to be used as an intensity sensor.

The CRD trace obtained with the proposed configuration is shown in Figure 2. The time of a single round trip is ca. 7.8 μs and is strongly dependent on the pulse width, fiber length, fiber losses, MMI losses and others.

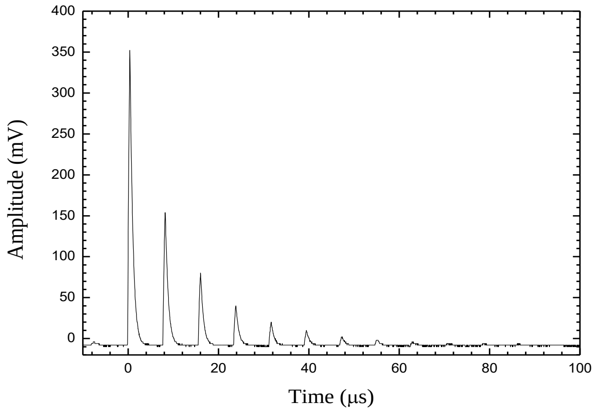
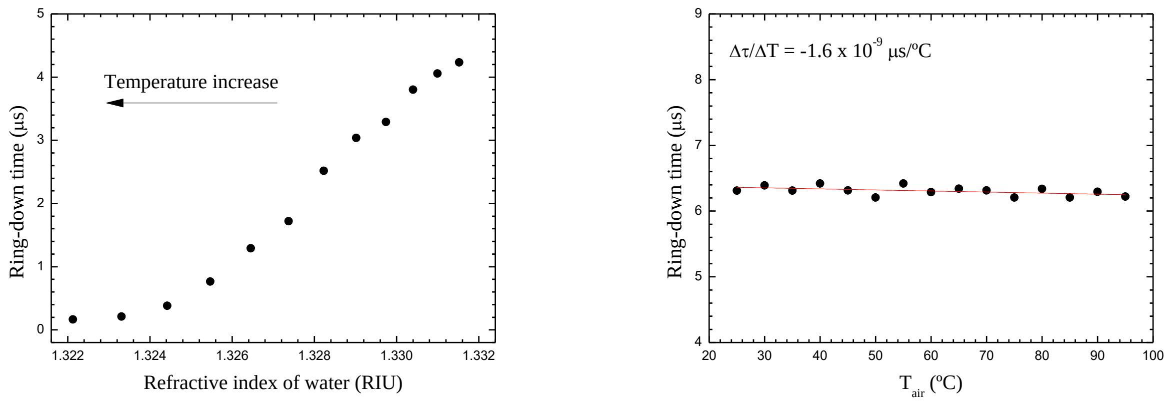


Figure 2. CRD trace for pulses sent by the modulated multimode laser source into the fiber loop with 500 ns width.

The behavior of the MMI-based fiber sensor as a refractometer was duly characterized. The sensing head was placed under water and submitted to increasing temperature in the range 25–80°C, with 5°C steps. The modulated laser source used in this experiment sent pulses at the operation wavelength of 1550 nm, which in turn is located in the slope of the band-rejection filter centered at 1546 nm (see Figure 1b). Therefore, the wavelength variation caused by RI changes of the external medium will shift the band-rejection peaks, associated with an amplitude variation of the acquired signal. In this case, the temperature-induced RI variation of water causes the amplitude of the band-rejection peaks to change and consequently leading to measurable losses in the acquired CRD signal. Figure 3a) presents the ring-down time variation according to temperature-induced RI changes of water.



(a) (b)

Figure 3. Ring-down time versus (a) temperature-induced RI changes of water and (b) temperature applied to the MMI-based fiber sensor integrated in the CRD system.

The ring-down time decreases with RI of water as a result of temperature increase, as shown in Figure 3a). Since the MMI-based fiber sensor is intrinsically sensitive to temperature but also to RI of the external medium, one had to remove the temperature component of the acquired output signal, in order to obtain the results presented in Figure 3a). Therefore, the behavior of the sensing head to temperature variation was studied. The MMI fiber sensor was placed in a furnace and submitted to increasing temperature in the range 25-95°C, with 5°C steps. A negligible sensitivity of -1.6×10^{-9} μs/°C was attained, as depicted in Figure 3b). This allowed eliminating the temperature component from RI measurement of water and a linear sensitivity of 580 μs/RIU in the RI range of 1.324-1.331was obtained.

3. CONCLUSIONS

Summarizing, an MMI-based fiber device was inserted in the fiber loop and interrogated by CRD Technique for measuring temperature-induced RI changes of water. The sensing head was based on multimodal interference, and relied on a (SMF – coreless-MMF – SMF) fiber configuration. Due to the high losses intrinsic of the MMI fiber structure, an EDFA was inserted in the fiber loop cavity in order to compensate them. This allowed obtaining an observable signal with a reasonable decay time. The behavior of the sensing head to temperature variation was also studied and a sensitivity of -1.6×10^{-9} μs/°C was attained. This allowed eliminating the temperature component from RI measurement of water and a linear sensitivity of 580 μs/RIU in the RI range of 1.324-1.331 was obtained. The MMI fiber sensor allowed achieving a sensitivity ~4-fold the one already reported with a tilted fiber Bragg grating.

ACKNOWLEDGMENTS

This work was supported by Project "CORAL – Sustainable Ocean Exploitation: Tools and Sensors, NORTE-01-0145-FEDER-000036, financed by the North Portugal Regional Operational Programme (NORTE 2020), under the PORTUGAL 2020 Partnership Agreement, and through the European Regional Development Fund (ERDF). S.S. received a Pos-Doc fellowship (ref. SFRH/BPD/92418/2013) also funded by FCT – Portuguese national funding agency for science, research and technology.

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