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Review

[INVITED] New advances in fiber cavity ring-down technology ☆

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A B S T R A C T

A brief review in the cavity ring-down technique (CRD) is presented. In this review, there will only be considered the conventional fiber CRD configuration, i.e., there will only be presented researches involving cavities with two couplers with 99:1 ratios, due to the large amount of publications involving this spectroscopy method. The presented survey is divided in different topics related to the measurement of physical parameters, such as strain and temperature, curvature, pressure, refractive index, gas and biochemical sensing.

Contents

1. Introduction

The cavity ring-down (CRD) technique consists in a spectroscopy method broadly used in technology. Being mainly employed in the sensor area, this methodology enables an accurate analysis of amplitude behavior over the time. Throughout the past decades, the CRD spectroscopy has been subject of a lot of research, namely in chemical and molecular analysis in real time [1]. The principle involved settles the basis for various configurations, being also applied to resonant optical cavities with high reflective mirrors, as a result of the high evolution of this technique [2,3]. Through association with the previous developed fiber loops, there were implemented new fiber optic-based CRD settings, which, in turn, used a fiber loop operating as the resonant cavity. This configuration quickly obtained a lot of popularity in the scientific community, mainly for presenting an effective alternative to the usual CRD configuration [4]. By virtue of these conceptual studies, the CRD technique has been target of a lot of research in the spectroscopy field, being implemented in the last decade to the measurement of physical parameters, such as strain [5–7], temperature [8], curvature [9,10] and pressure [11–13]. More recently, a fast development of CRD technique allied to the biochemical sensing field can also be easily recognized. The implementations in this area are quite extensive, which can go from detection of organic dyes [14] to unicellular organisms [15], or even 1-octyne in decane solution [16]. The CRD approach has also been widely used for refractive index of liquids [17–21] and gas sensing [22–25].

Along with the expansion in these areas, the CRD technique has

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also been practically reinvented, yielding the investigation of other areas, such as cavity-enhanced spectroscopy [4]. Due to the broad investigation, this technique has been extended being so reported many different functions using a Fiber Loop Ringdown (FLRD) [26]. Opening a micro hole in one of the fiber end faces, a significant reduction in the coupling loss was achieved [27]. In addition to these applications, the CRD technique use is widespread, being implemented in chemical sensors [28], using frequency-shifted interferometry [29], using wavelength-tunable ultrashort pulsed light [30] or even an Optical Time Domain Reflector (OTDR) instead of the usual implemented laser and modulator setup [31]. More recently, a new CRD topology for remote Sensing was demonstrated [32].

The employability of this technique is very wide, offering great flexibility and conferring immense possibilities on its use, such as in fiber loop sensing devices (including fiber Bragg gratings, long period gratings, fiber microchannels and photonic crystal fibers). These elements, when put together with the CRD technique, have allowed high resolution and high sensitive values, yielding huge developments in the optical fiber industry. Thus, pulses of high intensity and highly sensitive photodetectors or optical amplifiers within the cavity are commonly used. The spectroscopy method has shown great potential for high sensitivity detection, which led to a very wide range of applications in research laboratories. For this reason, a revision of the work made implementing these conventional structures is presented, in order to elaborate a complete study on this subject.

2. Theory

A fiber cavity ring-down operation lays down on a simple principle. The measurements obtained by adopting a conventional cavity ring-down technique are related to the injection of pulses into an extremely high-finesse bulk cavity, which can be achieved either through the use of reflective layers ($R > 99.9\%$) or simply by using fiber couplers of high split ratios (e.g. 99:1) [27]. In this review, there will only be considered the conventional fiber CRD configuration, i.e., there will only be studied cavities with two couplers with a 99:1 ratio (see Fig. 1). That way, the revision made is limited to the existent research involving this type of conventional structures. As represented in Fig. 1, the configuration operates as follows: port 1 is coupled in with port 3, by means of the first coupler, being the output port 4 recoupled as an input signal (port 5) with the input port 7, through the second coupler. Port 6 and port 3 are connected, forming the cavity ring-down structure. Port 8 is used as an output arm to interrogate the amplitude of the signal over time. The two couplers operate in distinct ways; one for the source and the other for measuring the intensity of the pulse, thus forming the analog of the mirrors in a traditional CRD. In the case of time resolved ring-down signals, the initially received intensity is very low, becoming even less with each round trip, due to the high split ratio of the couplers. However, the high reflectivity or coupling ratios are necessary to achieve large numbers of round trips (traveling more time inside the cavity).

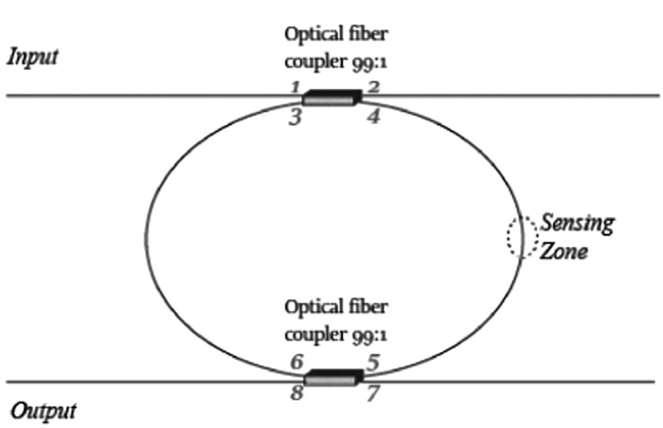

Fig. 1. Conventional cavity ring-down configuration.

The most important aspect in CRD technique is the independence of the output signal in relation to the power of the input signal, so that there is only output signal dependence with time. Due to the losses in the couplers and the fiber intrinsic attenuation, the pulse will slowly decay as it travels around the loop. The rate of decay of the output pulse train indicates the cavity loss. If the losses are not too significant, although only 1% of the input signal enters the cavity on the first trip, the pulse will still take several turns around the loop, being measured at a given position. Analyzing the signal through port 8, one then observes a series of pulses equally spaced in time, although with increasingly smaller intensities. This time frame can be directly obtained by the formula $t = nL/c$, where L is the length of the cavity, n the effective refractive index of the fiber and c the light velocity.

Let us consider the case when an intensity sensor, T_s, is placed inside the fiber loop, for the purpose of measuring a certain physical quantity. At every turn traveled by the pulse, it suffers attenuation by the same factor, caused by the fiber intrinsic attenuation, the couplers insertion losses T_c, and the sensor transmission T_s. At the end of the first loop, the relation between the intensity of the pulse after the first turn, I_1, and the initial one, I_0, is given by [14]:

$$\frac{I_1}{I_0}=T_s T_c^2 e^{-\alpha L} \tag{1}$$

After n turns, considering t_n the time for n turns, the relation between the intensity of the pulse, I_n, and the initial one is:

$$\frac{I_n}{I_0}=\left(\frac{I_1}{I_0}\right)^n=e^{(t_n/\Delta t)\ln(\frac{I_1}{I_0})}=e^{-t_n/\tau} \tag{2}$$

The time constant, τ, strongly depends on the losses in the fiber loop [14]:

$$\tau=\frac{L}{c\left[\alpha L-\ln T_s T_c^2\right]} \tag{3}$$

The principle involved in these sensing measurements are based on the dependence of the decay time with the sensor transmission. Since the pulse travels several times through the intensity sensor, high sensitivities can be achieved by using this technique. Fig. 2 shows the conceptual behavior of the amplitude of the pulse over time, expected on a conventional CRD configuration.

3. State-of-the-art for physical parameters measurement

3.1. Strain and temperature sensing

In 2004, Tarsa et al. [5] presented a CRD technique with a biconical tapered fiber incorporated in the fiber loop for strain sensing. It was demonstrated a minimum detectable change in ringdown time of 0.08%, corresponding to a minimum detectable displacement of 4.8 nm, and a sensitivity to strain as small as 79 $n\varepsilon/\sqrt{Hz}$ over a 5-mm taper length. Later, Ni et al. [6] used a long period grating instead inside the fiber loop to measure strain. By detecting the ringdown time at different strain levels, a high sensitivity of 1.261 $ns/\mu\varepsilon$ and a minimum detectable strain level of 9 $\mu\varepsilon$ could be achieved. Most recently, our research group [7] developed a CRD configuration for the measurement of strain. An