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Comparison of detection limit in fiber-based conventional, amplified, and gain-clamped cavity ring-down techniques

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ABSTRACT

Relative performance and detection limit of conventional, amplified, and gain-clamped cavity ring-down techniques (CRDT) in all-fiber configurations are compared experimentally for the first time. Refractive index measurement using evanescent field in tapered fibers is used as a benchmark for the comparison. The systematic optimization of a nested-loop configuration in gain-clamped CRDT is also discussed, which is crucial for achieving a constant gain in a CRDT experiment. It is found that even though conventional CRDT has the lowest standard error in ring-down time ($\Delta\tau$), the value of ring-down time (τ) is very small, thus leading to poor detection limit. Amplified CRDT provides an improvement in τ, albeit with two orders of magnitude higher $\Delta\tau$ due to amplifier noise. The nested-loop configuration in gain-clamped CRDT helps in reducing $\Delta\tau$ by an order of magnitude as compared to amplified CRDT whilst retaining the improvement in τ. A detection limit of 1.03×10^{-4} RIU at refractive index of 1.322 with a 3 mm long and 4.5 μm diameter tapered fiber is demonstrated with the gain-clamped CRDT.

1. Introduction

Cavity ring-down technique (CRDT) is a popular time-domain technique for measurements that require high sensitivity [1]. It has many significant industrial and bio-medical applications [2]. This technique is known for its advantages such as long effective path lengths, insensitivity to intensity fluctuations of the light source and above all, immunity to electromagnetic interference of the sensing set up [3]. CRDT was first used in 1980 to measure the reflectivity of highly-reflective mirrors [4] and later, for measurements of small cavity loss in free-space cavities [5]. Compared to free-space cavities, fiber-based cavities — consisting of a fiber loop (known as conventional CRDT) make the arrangement compact and portable, in addition to being alignment-free [6,7]. However, these cavities are affected by large inherent loss due to the insertion loss of components such as couplers and sample holders [8]. A suitable fiber amplifier was included in the fiber cavity to compensate this inherent loss and achieve long ring-down times and hence, improve detection limit [9]. An erbium doped fiber amplifier (EDFA) was used in this particular demonstration of amplified CRDT since the wavelength of operation was in 1530–1560 nm range. However, the pulse-to-pulse fluctuations in the gain and amplified spontaneous emission (ASE) noise of EDFA resulted in a reduction of the detection limit [10]. Post-processing techniques such as digital and adaptive filtering were suggested to remove the impact of ASE noise [11–13]. A nested-loop configuration (known as gain-clamped CRDT) was also suggested to provide a constant (clamped) gain for all pulses, using a laser loop instead of an amplifier in the fiber cavity [9,14].

Conventional [2,6,7,15,16], amplified [9–13,17], and gain-clamped CRDTs [8,9,14,18] have been implemented in the past for various applications, albeit independently. However, to the best of our knowledge, there has been no systematic comparison of parameters such as minimum detectable change in loss and detection limit, between the three techniques through experiments. In this paper, refractive index (RI) measurements of sugar solution are performed at a wavelength

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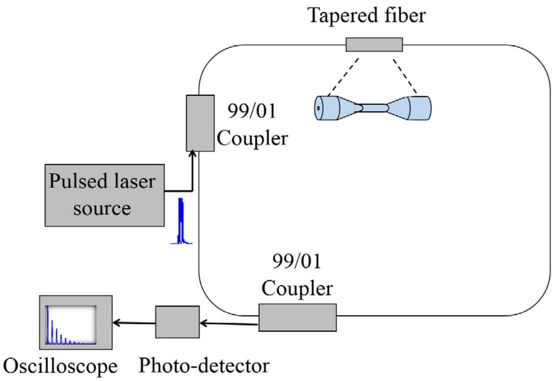

Fig. 1. Schematic of the experimental set-up of fiber-based C-CRDT.

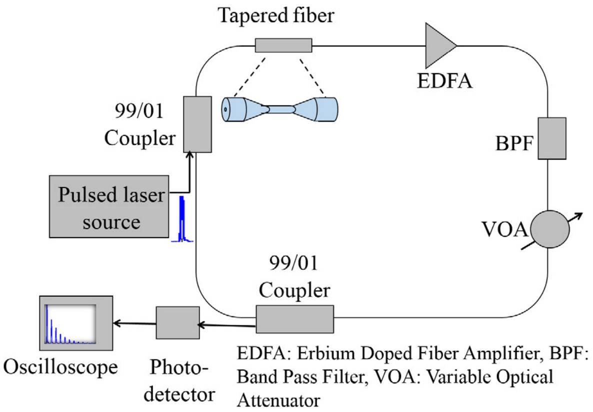

Fig. 2. Schematic of the experimental set-up of fiber-based A-CRDT. An erbium doped fiber amplifier (EDFA) compensate the intrinsic loss of the cavity.

of 1550 nm using uncoated tapered fiber as an intra-cavity element in the three techniques. These measurements are used as a benchmark to quantify and compare the relative performance and detection limits of the three techniques. Conventional and amplified CRDTs have been used in the past by others at a wavelength of 1550 nm [19,20] and by our group at a wavelength of 1953 nm [21], for refractometric sensing using tapered fibers in independent demonstrations. The evanescent field in tapered fibers helps in achieving good sensitivity [22], which is further accentuated when the tapered fiber is included as an intra-cavity element. Time-domain refractometric measurements using the evanescent field in tapered fibers thus combine the advantages of fiber-based CRDT and that of tapered fibers.

A nested-loop configuration is typically used in a gain-clamped CRDT for achieving a constant gain. Balancing the two loops for an optimal operation — especially for performing a CRDT sensing experiment is extremely challenging [14]. Some of the issues of the nested-loop are discussed in the literature [8,14,18] but a detailed procedure for its optimization is not available. In this paper, the systematic optimization of the nested-loop in gain-clamped CRDT is also discussed in detail.

2. Theory

In pulsed CRDT, light from a pulsed laser source is coupled into a high-finesse cavity. The time-dependent output of the cavity is monitored using a photo-detector and an oscilloscope to determine the cavity loss [1]. In a conventional fiber-based CRDT (referred to as C-CDRT henceforth), the cavity is constructed using two 99/01 couplers and a sample head (tapered fiber in this case), as shown in Fig. 1. A pulse is launched into the cavity using the first coupler. The power of this cavity ring-down (CRD) pulse decreases exponentially in each round-trip, based on the total loss of the cavity. The second 99/01 coupler is used to extract output of the CRD cavity. The time taken for the output of the cavity to decay to $1/e$ of its initial value is referred to as the ring-down time (τ), which is related to the total cavity loss (α) through [6]

$$\tau = \frac{t_r}{\alpha} = \frac{t_r}{\alpha_c + \alpha_s}, \tag{1}$$

where t_r is the round-trip time of the cavity. α_c refers to the inherent loss of the cavity, which includes the loss of couplers, splices, tapered fiber, and the absorption loss due to solvent in case of a liquid sample. α_s is the loss due to the sample absorption and is referred to as the sample loss. The envelope of the output pulses of the cavity is fitted with an exponential function to extract τ. For a given cavity, t_r and α_c are known; α_s is then calculated using (1). The effective number of round-trips — defined as the ratio (τ/t_r) [23], is limited by the inherent loss of the cavity in the case of C-CRDT.

A schematic of the experimental setup for amplified CRDT (referred to as A-CRDT henceforth) is shown in Fig. 2. An EDFA is additionally included in the cavity to compensate for the inherent cavity loss. A band pass filter (BPF) is used to filter the out-of-band ASE generated by the amplifier. In this configuration, the equation of ring-down time is modified as [9]

$$\tau = \frac{t_r}{\alpha} = \frac{t_r}{\alpha_c + \alpha_s - G}, \tag{2}$$

where G is the single pass gain of EDFA. The total loss in the cavity (α) is controlled by adjusting the gain, G (by varying pump power of EDFA). In order to maximize the ring-down time, the gain has to be adjusted such that almost all the loss except the sample loss is compensated. A variable optical attenuator (VOA) can be used to finely balance the gain and loss of the cavity. This is a sensitive adjustment, because an exact match of gain and the total cavity loss would lead to lasing in the cavity, which has to be avoided. A careful adjustment of G can significantly increase the ring-down time and the effective number of round-trips, which in turn improves the detection limit [24].

However, the EDFA induces pulse-to-pulse gain fluctuations since the power of the CRD pulse progressively decreases with each round-trip. Consequently, the noise due to ASE also fluctuates, thus degrading the performance of the system. CRDT in the gain-clamped configuration is used to maintain the constant gain experienced by the CRD pulse in each round-trip by replacing the amplifier shown in Fig. 2 by a laser loop. The schematic of experimental setup of the gain-clamped CRDT (referred to as G-CRDT henceforth) is shown in Fig. 3. It consists of two nested-loops - an outer loop (with solid lines) that constitutes the CRD cavity and an inner loop (with dotted lines) which is a laser loop that provides a stabilized gain to the CRD pulse propagating in the outer loop. The outer and inner loops are inter-connected using two 50/50 couplers, with an EDFA in common. The lasing wavelength (λ_{las}) propagating through the inner loop and the CRD pulse propagating at signal wavelength (λ_{sig}) in the outer loop share the same EDFA, thus enabling the gain experienced by the CRD pulse to be clamped by λ_{las}. An optical band pass filter (BPF 1 – with center wavelength at λ_{las}) is used in the inner loop to ensure that $\lambda_{\mathrm{sig}} \neq \lambda_{\mathrm{las}}$, to avoid cross-talk between the two loops [18]. A variable optical attenuator (VOA 1) is used to carefully adjust the gain in the EDFA at λ_{sig} such that it can compensate the inherent loss of the outer loop. The output of a pulsed laser source is coupled into the outer loop using a 99/01 coupler. The other components in this loop are tapered fiber, a second 99/01 coupler to extract the output of the CRD cavity, a band pass filter (BPF 2) and a variable optical attenuator (VOA 2). BPF 2 (with center wavelength at λ_{sig}) ensures that the wavelength propagating in the outer loop correspond to only λ_{sig} and VOA 2 is used to adjust the cavity loss of the outer loop, such that the outer loop does not lase. The outer loop has to be maintained just below the lasing threshold at λ_{sig} and the inner loop above the lasing threshold at λ_{las} [14]. When the inner loop is lasing, the gain (or inversion) in the EDFA remains constant i.e. gain clamping occurs at all wavelengths except for λ_{las}. This provides a constant gain to the CRD pulse in the