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Analysis of a novel sensor interrogation technique based on fiber cavity ring-down (CRD) loop and OTDR

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ABSTRACT

We present the analysis of a remote sensor based on fiber Cavity Ring-Down (CRD) loop interrogated by an Optical Time Domain Reflectometer (OTDR) taking into account both practical limitations and the related signal processing. A commercial OTDR is used for both pulse generation and sensor output detection. This allows obtaining a compact and simple design for intensity-based sensor applications. This novel sensor interrogation approach is experimentally demonstrated by placing a variable attenuator inside the fiber loop that mimics a sensor head.

1. Introduction

Among all spectroscopy methods, those based on cavity ring-down (CRD) technique has a significant potential in providing accurate analysis of amplitude behavior as a function of time [1,2]. Fiber cavity ring-down technique represents a new class of CRD configurations which uses a fiber loop as the resonant cavity and has been implemented in a wide variety of sensing applications ranging from the measurement of physical parameters (e.g. strain, temperature, pressure, voltage etc.) [3,4] to the refractive index measurement of liquids [5], biochemical sensing and molecular analysis [6,7]. This popularity of fiber CRD loop is mainly due to its robustness (all fiber based [8]) and flexibility (ability to use many types of sensor head inside the loop [9]).

In the previous literature, the sensor configurations based on fiber cavity ring-down technique differ from each other essentially by their implementation of the sensor head (used inside the cavity) and their approach in interrogating the time response of the cavity. Silva et al. introduced a novel concept in demonstrating CRD by using OTDR [10] and successfully implemented this technique to several applications (e.g strain sensing [11], curvature sensing [12], and remote sensing [13]). The inherent loss of the cavity itself due to high losses of the passive devices is a major limitation for CRD systems. In order to overcome this drawback, two new configurations (insertion of an optical amplifier in the cavity [14] and a simplified linear cavity using a single fibre coupler together with two mirrors [15]) have been recently studied.

In order to simplify the whole system, we presented and experimentally demonstrated a new configuration, where an OTDR is used for both transmit and receive parts of the interrogation system. In our approach, modifying the system so as to measure the sensor response by the OTDR and the correct interpretation of the OTDR display are of paramount importance. The former has been realised by using a circulator while for the latter, we exploited reference trace measurements in such a way that the dead zone effect has been removed. This process permits the use of significantly shorter cavity lengths.

The main contribution of this article is the exploitation of a compact, off-the-shelf device (OTDR) together with the original post processing steps for the purpose of fiber CRD interrogation. Being complementary to the work of Silva et al., the study presented in this paper will serve to design appropriate interrogation configurations (pulse width, measurement range, dynamic range of sensor attenuation, etc.) before the development of application-specific sensor heads. The particular envisaged applications would be related to environmental monitoring systems where long measurement range of OTDR is exploited.

This paper is organized as follows: in Section 2, the principles of the proposed sensor system are explained. The parameters as well as the performance limits of our technique are then experimentally demonstrated in Section 3. Finally, the main conclusions of the work are reported in the last section.

2. Sensor principle

The presented sensor is based on the association of two parts: fiber Cavity Ring Down (CRD) and Optical Time Domain Reflectometry (OTDR). Fiber cavity together with an included sensing head acts as sensing platform whereas the OTDR is used as the interrogating device (cf. Fig. 1).

In its simplest form, the CRD is a fiber loop constructed by placing

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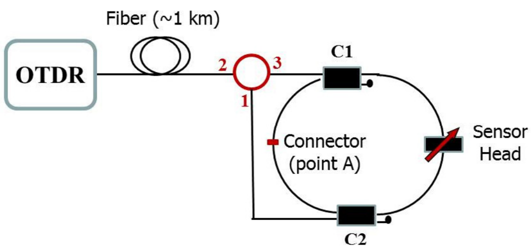

Fig. 1. Proposed sensor interrogation method with fiber CRD loop and OTDR.

two optical couplers directing (extracting) input (output) optical pulses into (from) the loop as represented in Fig. 1. Depending on the coupling ratios, a fraction of the incoming optical pulse circulates inside the loop until the light power decreases to the low levels. Each time the pulse is making a complete cycle through the loop, the second coupler extracts certain portion of the incoming pulse (to measure the light power) towards the detection unit (i.e. OTDR). The sensor head is inserted inside this loop and contributes to the total power attenuation.

The key element of the system making the connection between the CRD and OTDR is the optical circulator which sends the OTDR pulses to the first coupler (port 2 → port 3), and re-directs the pulses to be measured toward the OTDR (port 1 → port 2). The circulator blocks the signal on the counter clockwise direction. Therefore, it prevents the undesired reflections and Rayleigh backscattering signal from superposing on the pulses.

During each round trip through the loop, the optical pulse is exposed to fiber attenuation, the insertion losses of couplers, and the attenuation imposed by the sensor head. As a result, the pulse power will experience an exponential decay that can be expressed as

$$P = P_0 \exp^{-\frac{Ac}{nL}t} = P_0 \exp^{-\frac{t}{\tau}} \tag{1}$$

where P_0 is the pulse power at the input of the fiber loop; A,c,n, and L, are total loss, speed of light in vacuum, effective refractive index of the fiber, and total length of the fiber loop; τ represents the *ring-down time* (or *decay time*, $\tau = \frac{nL}{Ac}$).

As stated before, the optical source of the OTDR injects short optical pulses at a specific wavelength, and pulse width through the fiber bobbin and circulator. The latter directs the pulse to the coupler-1 which, in turn handles the signal into the fiber loop with a certain insertion loss (IL_{c1}^{direct}). When the pulse arrives at the coupler-2, a fraction of the pulse (imposing an insertion loss of IL_{c2}^{cross}, determined by coupling ratio and the excess loss of the coupler-2) is sent to the OTDR by passing through the circulator (port 1 →port 2) while the rest of the pulse (subject to an insertion loss of IL_{c2}^{direct}) continues its way through the coupler-1.

The power of the first pulse arriving at the OTDR in this way can be expressed as

$$P^{(1)} = loss_f P_0 IL_{crc23} IL_{c1}^{direct} a_{sens} IL_{c2}^{cross} IL_{crc12} \tag{2}$$

where P_0 is the initial power of the pulse injected into the system; IL_{crcXY}, and $loss_f$, respectively, the insertion loss of circulator (port$_X$ → port$_Y$), and the total loss of fiber bobbin; a_{sens} stands for the attenuation factor of the sensor head. This first pulse does not contain useful information about the decay rate of the pulse train and discarded in our time analysis.

Starting from the second round, there will be a series of pulses arriving at the OTDR detector indicated as P_{OTDR} which is given by

$$P_{OTDR}^{(k)} = P^{(1)} (IL_{c2}^{direct} a_{sens} IL_{c1}^{cross})^{(k-1)}; k = 1,2,... \tag{3}$$

The temporal signature of the CRD loop as stated in Eq. 3 is fed into the OTDR's receiver where the optical power of this test signal is measured as a function of time. After some internal signal processing, the OTDR display shows a vertical scale of the pulses in dB (5log) and a horizontal scale of distance in km. The interpretation of such a signature, however,

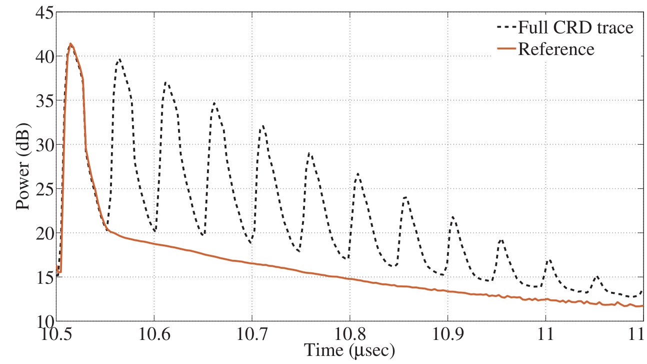

Fig. 2. Typical fiber cavity ring-down loop decay waveform and the reference trace, both obtained by the OTDR. Reference trace is measured by disconnecting the fiber loop at *point-A* (cf. Fig. 1).

requires attention in three aspects as the OTDR in this configuration is not used in a classical way.

- Distance and power axes should be both scaled up by a factor of 2 as the OTDR divides the time and power base by 2 (the light travels and attenuates twice over a given distance in a conventional OTDR measurement).
- The fit function on the decaying peaks should be a linear line rather than an exponential envelope as the OTDR provides measurements in dB.
- The effect of the exponential decaying edge of a measured pulse on the successive pulses should be removed from the OTDR trace before applying the fit function. This effect for the first peak ($P^{(1)}$) that has been measured by disconnecting the fiber loop at point-A (cf. Fig. 1) is represented in Fig. 2. Even though this first pulse is discarded in the time analysis, the offset created by the diffusion tail of it should be eliminated.

3. Experimental work and discussion

The measurements were performed by using the CRD loop interrogated by a commercial OTDR (cf. Fig. 1).

A single mode fiber (SMF 28) of 1070m in length was placed between the OTDR and the cavity. The OTDR parameters were set as follows: wavelength of 1550 nm, distance range of 2.5 km and averaging time of 30 s.

An example OTDR trace including the feeder fiber and the decaying pulse peaks is shown in Fig. 3 (before scaling the axes by two). The total length of the fiber cavity is set to ~ 10 m (comprised of the patchcords between passive components inside the loop).

The OTDR enables launching pulses with a variety of pulse width which is an important parameter to be taken into account during the experiments. Lower pulse width provides us with a better spatial resolution at the expense of smaller dynamic range (due to lower energy).

The measured decaying pulse trains obtained with three different pulse widths are shown in Fig. 4. Due to relatively short measurement distance in our implementation, almost all pulse energy is dedicated to the fiber loop. Hence, the smallest possible value (5ns) that can be obtained by our OTDR (EXFO FTB 7300E OTDR module on FTB-500 Mainframe operating at 1550 nm and 1625 nm) has been used for the rest of the measurements. At this smallest possible pulse width, which is still comparable to the cavity length, the overlapping between the trailing edge of the previous pulse with the next pulse has been eliminated as explained above.

Inside the fiber loop, a variable optical attenuator was used as a *sensor head* which was calibrated to six different attenuation values by the way of a separate point-to-point link. During calibrations, each attenuation measurement was repeated ten times and a precision value of

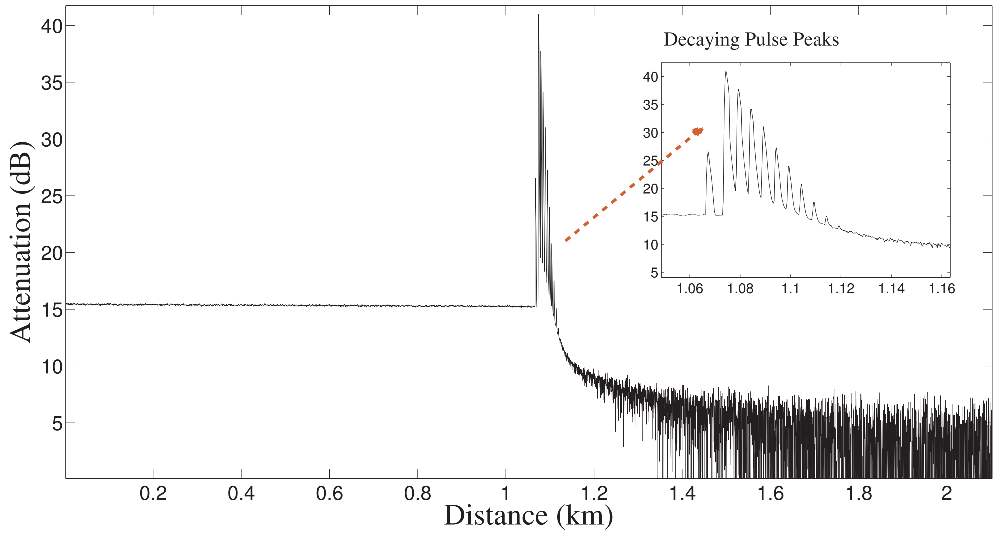

Fig. 3. Full OTDR trace including the feeder fibre and the decaying pulse peaks. Inset: zoom on the decaying peaks.

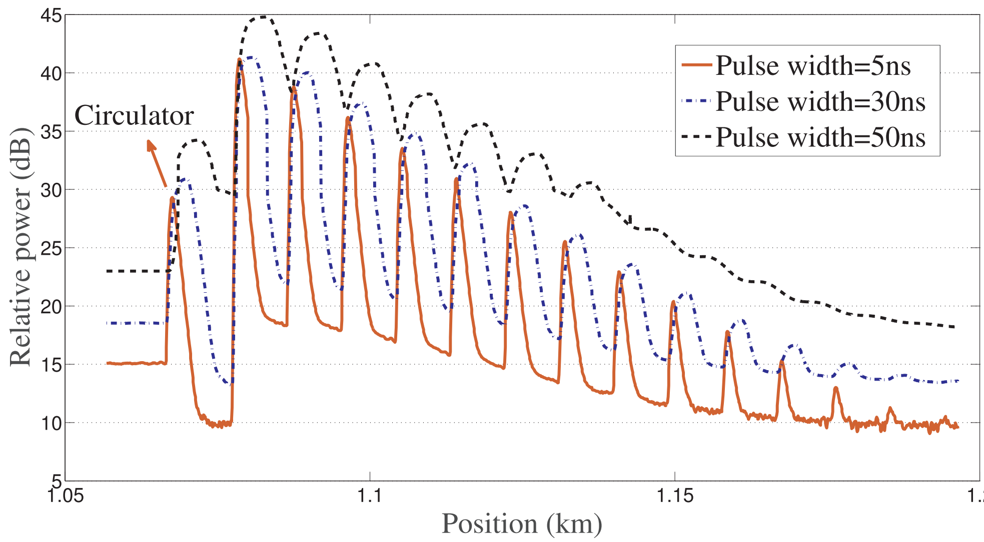

Fig. 4. Decaying pulses on the OTDR trace for diverse pulse widths.

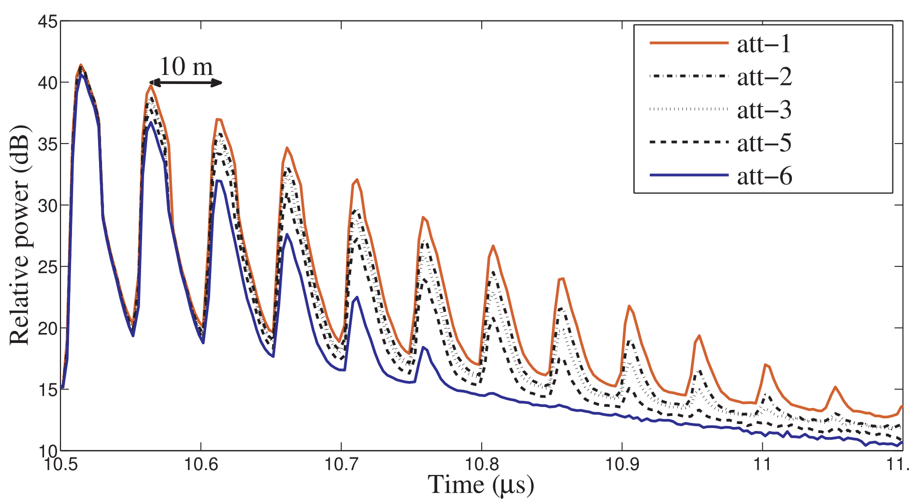

Fig. 5. Decaying pulse peaks for five different attenuation values inserted into the fiber loop (*x*-axis is properly converted into time domain).

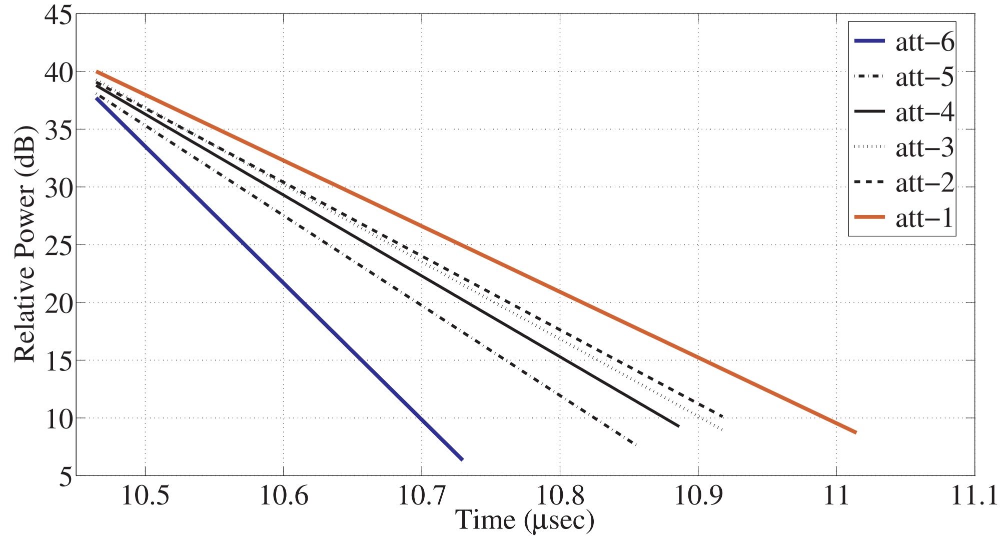

Fig. 6. Fit lines for different attenuation values inserted into the loop (after offset elimination).

Table 1
Comparison of the measured slope values obtained on OTDR traces for six different attenuation levels of the sensor head.

Screw position	Attenuation level [dB]	Mesured slope [db/ns]
att-1	0.68	9.92
att-2	1.25	11.22
att-3	1.56	11.51
att-4	1.93	12.27
att-5	2.35	13.50
att-6	3.32	16.80

± 0.18db was obtained. As shown in Fig. 5, a total number of 13 peaks (red peaks) can be observed when *att-1* (0.68 db) is inserted in the CRD loop, whereas this number is reduced to only 6 peaks (blue peaks) for the *att-6* (3.32 db). In other words, a higher attenuation value means a faster *decay rate* ($1/\tau$) or a shorter *decay time* (τ).

Once calibrated, the variable attenuator inside the fiber loop was tuned to generate different attenuation levels. Each attenuation level gives rise to a corresponding slope value on the fitted line of decaying peaks (after offset removal) as shown in Fig. 6.

These slopes, being proportional to the decay rates, are listed in Table 1. Based on these values, the response of the proposed sensor interrogation approach is characterized in Fig. 7 showing a sensitivity of 13.46 ± 1.38 ns/dB. This behaviour observed on Fig. 7, between the attenuation value (which mimics the sensor response in our case) and the decay time calculated from the corresponding fitted line, successfully demonstrates the feasibility of using OTDR-based fiber CRD technique as a sensor interrogation tool. Minimum detectable optical loss has been calculated as 0.3 db.

4. Conclusion

The optical fiber sensors have been fast becoming popular in many new application areas (e.g monitoring of environmental conditions, railways, mines, etc.). The wavelength range implemented in most of such domains is within the classical telecommunication wavelength region as the commercial opto-electronic devices are readily available with reasonable prices. OTDR is one of these equipments that can find applications in both telecommunication networks and optical fiber sensors [16].

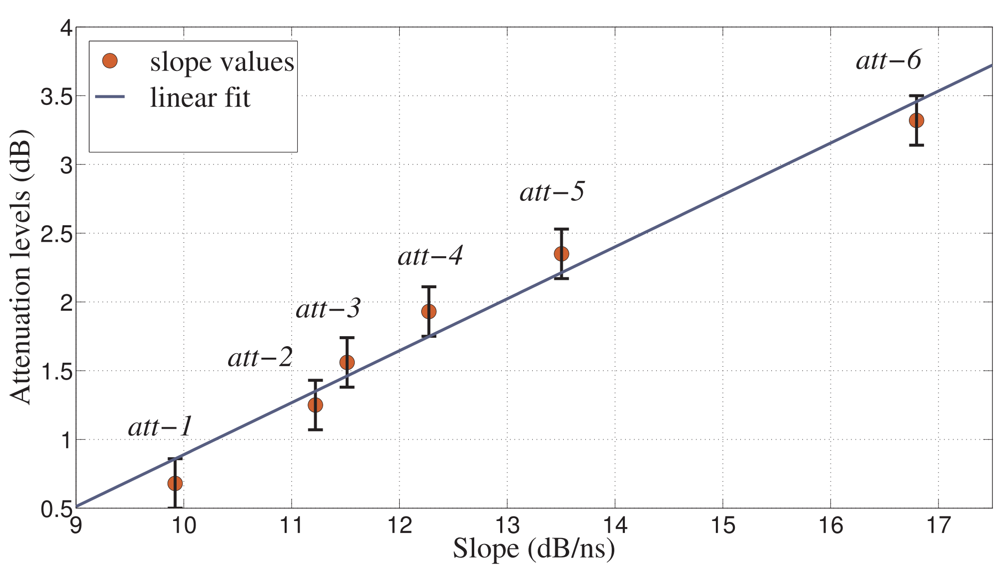

Fig. 7. Response of the proposed sensor: relation between the measured slopes (proportional to the *decay rate*, $1/\tau$) and the attenuation level of the sensor head (variable attenuator). Error bars indicate 0.18db of precision on the attenuation values obtained from repeatability tests.

In this study, a new configuration of a previous OTDR-based CRD interrogation technique [17] has been proposed. A conventional OTDR and its readily available signal processing tools have been implemented. We experimentally demonstrated this fast and simple approach by employing a variable attenuator to mimic the effect of a sensor head. Using our original post processing method, the unwanted signature of the photodetector response on the measured pulses has been successfully eliminated. As a result, the spatial resolution provided by the commercial OTDRs become sufficient to interrogate the fiber loops with lengths down to about 10 m. Next step will be the optimisation of the detection limit showing the implementation of the proposed system in a practical application.

Its fast and linear response makes the proposed system a perfect candidate for diverse sensor applications requiring the self-calibration, easy implementation, and remote monitoring features, particularly those in difficult environments.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, athttp://dx.doi.org/10.1016/j.yofte.2018.04.005.

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