Cavity ring-down technique for remote sensing A proof-of-concept for displacement measurement

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ABSTRACT

This work demonstrates the viability of using a cavity ring-down technique (CRD) for remote sensing. A conventional CRD configuration is used where and optical circulator is added inside the fibre loop to couple 20 km of optical fibre with a gold mirror at its end with the purpose of remote sensing. As a proof-of-concept, an intensity sensor based on an eight-figure configuration is used at the end of the 20 km of fibre for displacement sensing. In this case, a commercial OTDR is used as modulated light source to send impulses down to the fibre ring.

Keywords: Cavity ring-down, displacement, optical fibre sensors, remote sensing

1. INTRODUCTION

The optical time domain reflectometer (OTDR) was one of the first equipment to be used for remote sensing. The OTDR is a commercial device widely used for measuring losses along several kilometers of optical fibre, by detecting the loss of the Rayleigh backscattered light [1]. Early it was shown to be a promising device in measuring point-by-point losses, by using intensity sensors along the fibre. Several works have been reported in this area of research, where an OTDR is used to monitor sensors such as fibre Bragg gratings (FBGs) [2], long period gratings (LPGs) [3], multimode interference (MMI) [4], fibre loop mirrors [5] and others. One of the main advantages is the quasi-distributed monitoring along 100 km of fibre without the use of amplification [1]. Currently, optical fibre sensors for remote sensing rely on non-linear effects [6].

However, one of the main disadvantages of this type of configuration is the use of expensive equipment. Cavity ring down (CRD) is a well-known technique for monitoring intensity sensors and relies on the measurement of the decay time of an impulse travelling inside a fibre ring [7]. One of the main advantages of the CRD technique is that the ring-down time is independent of the input power of the modulated light source.

In this work it is intended to demonstrate the viability of using a CRD technique for remote sensing. As a proof-of-concept, an intensity sensor based on an eight-figure configuration is used at the end of several kilometers of optical fibre for the purpose of displacement sensing. In this case, a commercial OTDR is used as modulated light source to send impulses down to the fibre ring.

2. EXPERIMENTAL SETUP

The schematic of the CRD configuration proposed for remote sensing is presented in Figure 1. The basis of the fibre CRD configuration proposed for remote sensing relies on the operation principle of the conventional CRD technique as follows: a modulated multimode laser source (centered at 1550 nm) send pulses into a fibre loop, i.e., the resonant cavity, which is formed by two optical fibre couplers with a 99:1 ratio each. The two optical couplers operate analogue as the mirrors in a traditional bulk 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 optical couplers. However, the high reflectivity or coupling ratios are necessary to achieve large numbers of round trips (traveling more time inside the cavity). Therefore, the pulses enter into the fibre loop by means of 1% arm of the input coupler (1) and ring around inside the cavity. The amplitude of the pulses will slowly decay as it travels around the loop, due to losses in the fibre loop caused by fibre splices, insertion losses of the fibre couplers, and fibre intrinsic attenuation of 0.12 dB/m over 20 km (see Figure 1).

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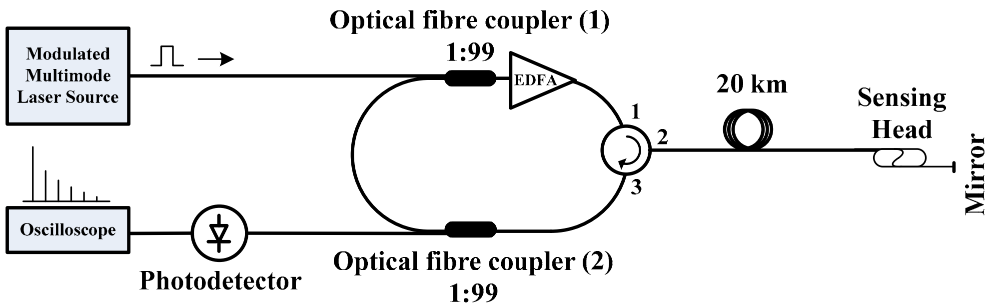

Figure 1. Schematic of the cavity ring-down configuration developed for remote sensing.

Experimentally, the losses in the cavity were found to be very high so that the ring-down trace was not observable. To overcome this limitation, an Erbium Doped Fibre amplifier (EDFA) was inserted in the fibre loop (see Figure 1) to provide an observable signal with a reasonable decay time. The EDFA was made in lab and comprises 2 m of an erbium-doped optical fibre with losses of 14 dB/m at 980 nm. An amplification signal with 1.85 dB gain was applied to the several pulses traveling inside the cavity. For the purpose of demonstrating remote sensing, an optical circulator was placed inside the fibre loop and connected to ~20 km of optical fibre, whose end is coated with a gold thin film to form a high reflectivity mirror. Therefore, each pulse that enters in the cavity by means of 1% arm of the input coupler (1) is directed to the optical circulator (port 1), travels 20 km of optical fibre and is back-reflected at the mirror, thus returning to the fibre loop (port 3 of the optical circulator). From here, the behavior is of a standard cavity ring-down, where the train of pulses rings around the fibre loop, with a decay rate given by the losses of the fibre-based system, being then coupled out via 1% arm of the output coupler (2). The output signal passes through a photodetector (gain of 40 dB) and the amplitude of the signal over time is monitored in an oscilloscope. As a proof-of-concept of the remote sensing, an intensity-based sensor was added after the 20 km of fibre and before the mirror, in order to perform displacement measurements (section 4).

3. OUTPUT SIGNAL ANALYSIS

In the proposed configuration, the OTDR was used to send pulses down into the fibre loop. The output signal passes through the photodetector and is converted into an electrical signal that is observed in the oscilloscope. The resulting waveform is strongly dependent on the pulse width, fibre length, fibre losses, and others. In this case, the pulse width was changed (considering other parameters constant), from 20 to 2 µs, and the resulting waveforms are depicted in Figures 2 a) and b), respectively.

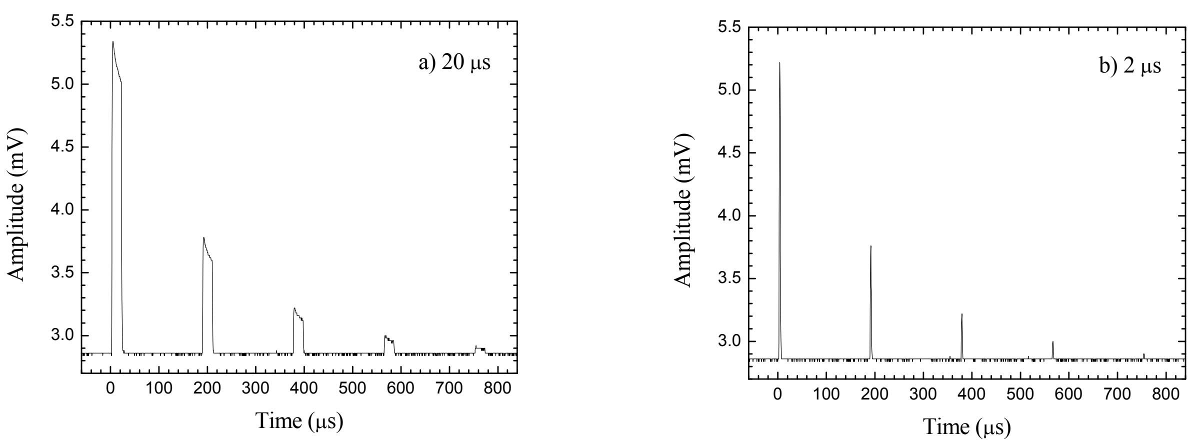

Figure 2. Waveform of the output signal obtained by an input pulse sent into the fibre loop with a) 20 µs and b) 2 µs width.

For a pulse width of 20 μs (Figure 2a), the output signal is saturated and 5 amplitude peaks are observed. This waveform has a ring-down time of ca. 130.5 μs. The time for a single round trip is ca. 188 μs which corresponds to ~38.4 km – this value was found by considering $L = ct/n$, where L is the fibre length of the configuration, c is the velocity of light and n is the core refractive index of the singlemode fibre used. Notice that, in this case, light travels ~20 km of fibre as is back-reflected by the gold coating mirror, thus the effective travelled length is about 40 km. Figure 2b) shows the waveform when a pulse width of 2 μs is sent into the fibre loop. Saturation of the signal is no longer observed, however, because of the fibre length of such configuration, the 5 observable peaks are better visualized in the case of signal saturation (pulse width of 20 μs). In this case, the waveform has a ring-down time of ca. 136.9 μs and the time for a single round trip is also 188 μs (fibre length is the same).

Figure 3 presents the pulse width versus ring-down time obtained for the CRD configuration proposed for remote sensing. The non-linear behavior results from the fact that less amplitude peaks are observable by decreasing pulse width, thus increasing the ring-down time of each waveform.

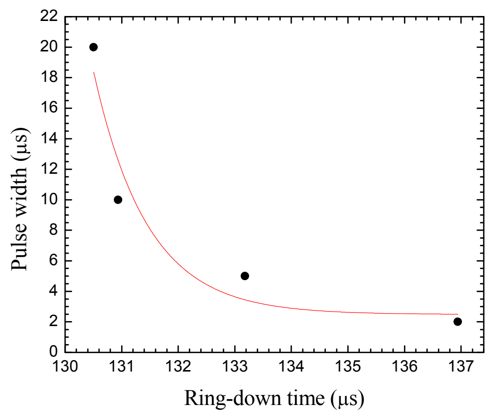

Figure 3. Pulse width versus ring-down time obtained for the CRD configuration developed for remote sensing.

4. REMOTE SENSING

To demonstrate the feasibility of measuring a physical parameter by remote sensing, an intensity sensor head based on an eight-figure was placed at the end of the 20 km of fibre and before the gold coating mirror. This simple sensor configuration was used as proof-of-concept. In practice, any other king of intensity sensor may be used, such as the long period grating, fibre Bragg gratings, fibre tapers, micromachined fibres, and others. In this approach, a pulse width of 20 μs was used (see Figure 2a) to send pulses down into the fiber loop due to the possibility of better observing the 5 amplitude peaks. To perform displacement (ΔL) measurements, the eight-figure was increasingly tightened (via sequential 5 mm steps), which corresponded to an increase of ΔL. The result was the amplitude decrease of the output peaks when applying displacement to the sensor (i.e., tightening the eight). The ring-down time for each waveform was measured and its variation as a function of displacement ΔL is presented in Figure 4. The observed behavior is due to the fact that tightening the eight-figure causes amplitude peaks to gradually decrease and disappear, thus, originating the ring-down time decrease with increasing displacement as well as the non-linear behavior. Recall that, for the case of no displacement, the waveform is limited to only five peaks whose amplitude rapidly decreases for small variations of the intensity sensor. Maximum displacement was found to be at 25 mm, corresponding to a waveform with only three observable peaks. Afterwards, the ring-down time was not measurable.

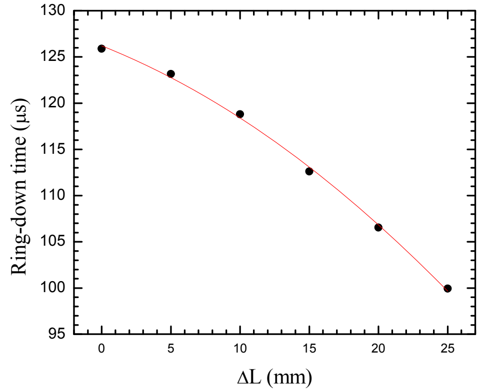

Figure 4. Ring-down time versus displacement applied to the intensity–based sensor.

5. CONCLUSIONS

Concluding, it was demonstrated the viability of using CRD technique for remote sensing. A conventional CRD configuration was developed where and optical circulator was added inside the fibre loop to couple 20 km of optical fibre with the purpose of remote sensing. As a proof-of-concept, an intensity sensor based on an eight-figure configuration was used at the end of the 20 km of fibre for displacement sensing.

6. ACKNOWLEDGEMENTS

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