High visibility phase-sensitive optical time domain reflectometer for distributed sensing of ultrasonic waves

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ABSTRACT

In structural health monitoring, the propagation of ultrasonic waves along a structure can reveal interesting data relevant to the integrity of the whole structure. The availability of a system for distributed sensing of ultrasonic waves could, in some cases (e.g. pipelines) provide extremely valuable information to civil engineers. Phase-sensitive optical time domain reflectometry (ϕOTDR) is a simple and effective tool allowing the distributed monitoring of vibrations along single-mode fibers. Up to now, ϕOTDRs have been used mostly for the measurement of sub-kHz vibrations. In this work, the authors present an experimental characterization of a high-visibility ϕOTDR and its performance when used for ultrasonic vibration measurements. The sensor was able to measure vibrations of up to 39.5 kHz with a resolution of 5 m over a range which could go up to 1.25 km. This is the first time to our knowledge that a ϕOTDR is demonstrated for distributed measurement of ultrasonic waves.

Keywords: Phase-sensitive OTDR, distributed sensor, optical fiber sensors, vibration measurements

1. INTRODUCTION

Fiber optic distributed sensing technology offers clear advantages over conventional point sensors when the number of points to be analyzed along a structure reaches several hundred [1]. In these cases, distributed sensors should normally be preferred due to their low cost per monitored point, their simple arrangement and the geometric versatility of optical fibers. Distributed fiber sensors nowadays allow performing different types of measurements at any point along a fiber (strain, temperature, vibration, pressure, etc). Among the distributed sensing techniques, Optical time domain reflectometry (OTDR) was first demonstrated over three decades ago [2, 3] and is now a commonly used technique for distributed measurement of losses along the fiber (fiber attenuation, optical components, broken points, etc), conventionally allowing the characterization and fault location in fiber-optic links and networks.

Traditional OTDRs use incoherent light and therefore can only measure intensity variations along the fiber. In a phase-sensitive OTDR (ϕOTDR) however, a pulse of highly coherent light is injected into a conventional single-mode fiber and the light reflected from different scattering centers interferes coherently to produce the detected optical power trace [4-7]. Because the position of these scattering centers is random, the ϕOTDR trace typically has random oscillations. This random pattern remains constant if the scattering centers do not suffer any change. However, in the case of localized vibrations, the trace shows variations synchronized with the vibration frequency. Due to its potential for fully distributed measurement of vibrations which can be used to monitor intrusions over large perimeters, ϕOTDR attracted considerable attention for more than two decades [8]. In fact, these sensors have been demonstrated in field tests, demonstrating enough sensitivity to detect people walking on top of a buried fiber [4]. In the literature, conventional ϕOTDR systems have been shown to allow the distributed measurement of vibrations of up to 1 kHz with a resolution of 5 m and dynamic range of a few tens of kilometers [5, 6]. Trustworthy vibration measurements can only be achieved with a good visibility and high signal-to-noise ratio (SNR) in the trace. The increase of the input pump peak power will increase the dynamic range and SNR of a ϕOTDR, but it is limited due to the onset of nonlinear effects [9]. As for the visibility of the trace, it will remain high if the coherence of the input laser is high and remains so all along the fiber. In temperature sensing, by analyzing the cross-correlation of ϕOTDR traces with different input wavelength pulses, temperature and strain measurements have also been demonstrated [7].

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In vibration-based structural damage identification or monitoring, ultrasonic waves are sometimes used to detect damages in the structure. These waves can reach frequencies going from several kHz to MHz. A distributed vibration sensor with capacity to detect these waves can therefore be required for these applications. In this work, the authors present an experimental characterization of a high-visibility ϕOTDR and its response when used for ultrasonic vibration measurements. The ϕOTDR trace was shown to have high visibility over a minimum of 9.9 km. As for the vibration sensing, the optical power variations of the ϕOTDR trace were shown to be synchronized with applied mechanical vibrations. The sensor was able to measure vibrations of up to 39.5 kHz, limited by the sampling frequency, with a resolution of 5 m in a demonstrated range of 600 m which could go up to 1.25 km. If the range is reduced, the system could be used to read even higher frequencies.

2. EXPERIMENTAL SETUP

The experimental setup used to characterize the visibility of the ϕOTDR (shown in Fig. 1 a), is based on a minor adaptation of the setup presented in [9]. The input pump power was adjusted to achieve the best performance and avoid nonlinear effects. A highly coherent laser diode (LD) (linewidth of 1.6 MHz) emitting at 1546 nm was used as the light source. An optical isolator (ISO) was placed at the laser output to avoid disturbances in the laser coherence due to back-reflections. A semiconductor optical amplifier (SOA), with rise/fall times in the order 2.5 ns, driven by a waveform signal generator (SG) was used to create 50 ns almost square pulses. A polarization controller (PC) was placed before the SOA to optimize the modulation properties and avoid any polarization sensitivity issue. Between the signal pulses, the SOA was negatively biased so as to enhance the extinction ratio (ER) of the delivered pulses. An ER of >50 dB was achieved this way. In this configuration, the ER has a very high impact in the SNR of the detected trace. In order to minimize the effect of the Amplified Spontaneous Emission (ASE) added by the Erbium-Doped Fiber Amplifier (EDFA), we inserted a tunable fiber Bragg grating (FBG) working in reflection. The spectral profile is the typical spectrum of a 100 % reflection FBG and its spectral width is 0.8 nm. Before being coupled into 9.9 km of SMF-28 fiber (FUT), light passed through an attenuator, which allowed varying the input power in the fiber. The average optical input power was measured at this position using a calibrated tap coupler (not shown in the figure) and the signal back-reflected from the fiber was recorded with a 125 MHz photo-detector and a high-speed digitizer.

The main picture of Fig. 1 b shows a ϕOTDR trace recorded with an input pump peak power of ~400 mW. In the inset figure the same spectrum is shown but the losses along the fiber have been numerically eliminated to improve the visualization. The trace displays the expected random oscillations around the average reflected power. The top figure shows the visibility of the ϕOTDR interference signal along the fiber, calculated as indicated in the figure caption. Despite the fact that the amplitude of the oscillations and average reflected power decrease exponentially along the fiber due to the losses, the interference does not loose contrast along the propagation (the visibility remains close to 1). Since the sensitivity of the ϕOTDR depends on the visibility of the interferences, we can conclude that it remains high along the complete fiber length.

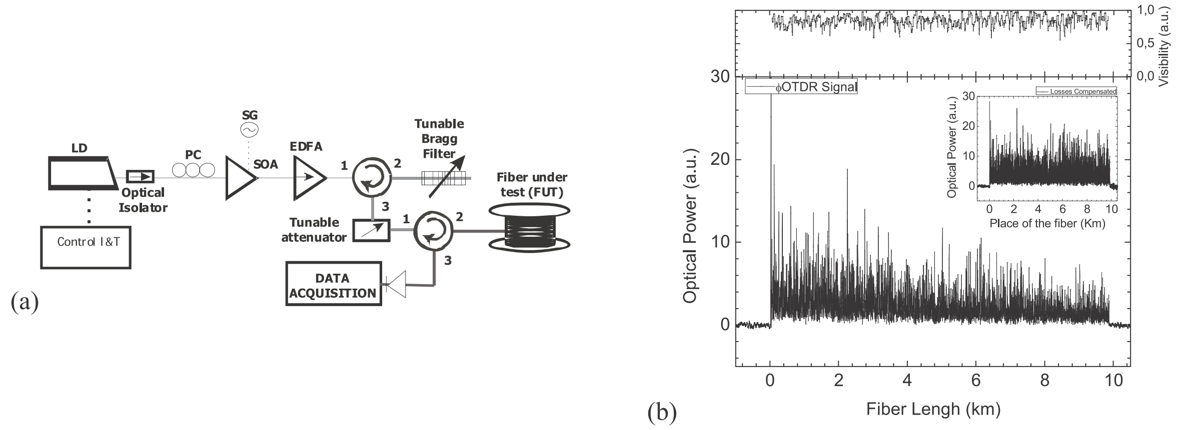

Figure 1. (a) Experimental setup: LD: Acronyms are explained in the text. (b) ϕOTDR interference signal along the FUT for an input pump peak power of ~400 mW (inset figure: same ϕOTDR signal where losses along the fiber have been eliminated to improve visualization). The top figure shows the visibility of the ϕOTDR interference signal. The visibility is computed as $V=(T_{max}-T_{min})/(T_{max}+T_{min})$ where T_{max} and T_{min} are the maximum and minimum values of the trace over a window of 40m.

3. VIBRATION MEASUREMENTS

Vibration measurements are carried out by measuring consecutive traces and obtaining the power evolution as a function of time in each point along the fiber. The sampling frequency at each position corresponds therefore with the frequency at which the pump pulses are launched into the fiber, which is limited by the maximum length that can be inspected. As an example, to monitor 1 km of fiber requires that the pulse repetition rate is below 100 kHz, which limits the maximum readable frequency at each position to 50 kHz. For the ultrasonic vibration measurements, the FUT was replaced with 600 m of SMF-28. Due to the limited re-trigger capability of our acquisition system, the pulse repetition rate could not be made larger than 80 kHz and therefore the maximum readable frequency corresponds to 40 kHz as given by Nyquist theorem. The far end of the fiber (around meter 590) was glued with tape inside a PVC tube 2 m long and 0.08 m of diameter in which mechanical vibrations of different frequencies were applied using a small vibration exciter with a maximum bare table acceleration of 736 ms^{-2} (with a 75 g mass attached). The optical power variation of the ϕOTDR signal was monitored for the meter 590 (inside the tube) along consecutive traces. We started by using a 20 Hz vibration and monitoring with a sampling rate of 20 kHz during 5 s with no post-processing. The first 500 ms of the optical power variation are presented in fig. 2 a. A clear pattern with peaks synchronized with the applied frequency is observed. The Fast Fourier Transform (FFT) of the optical power variation is presented in fig. 2 b. A clear peak at 20.3 Hz appears, as well as smaller peaks in the second harmonic (40.6 Hz), and multiples of half of the fundamental frequency (10 Hz, 30 Hz). This nonlinear behavior is partly related to the non-linear response of the ϕOTDR itself and also to the mechanical response of the tube. Anyway, given the amplitude difference between the peaks, it can be envisaged that to some extent this nonlinearity can be corrected if the input stimulus is not too big. Considering the input pump pulse width (50 ns) the expected resolution should be of 5 m. This is in agreement with our measurements since when the meter monitored was more than 5 m away from the fiber position inside the tube, the optical power variations and respective FFT no longer showed sensitivity to the applied vibrations.

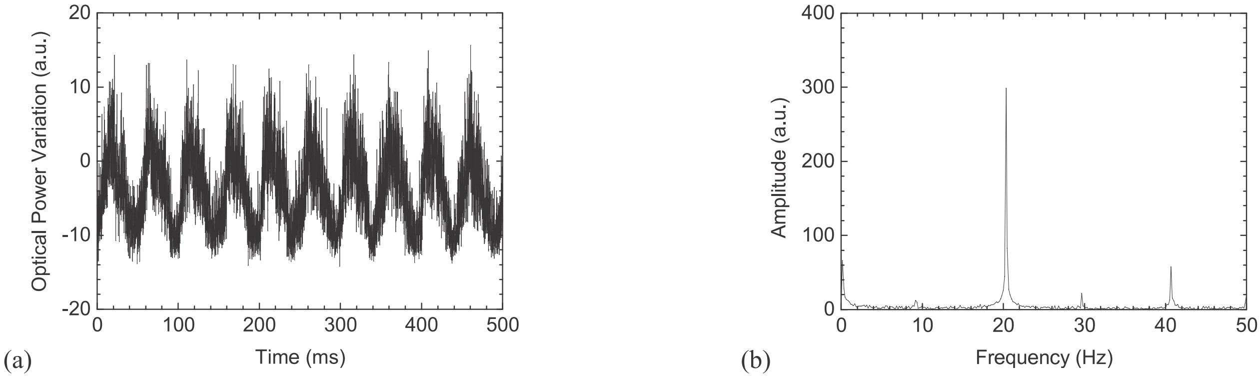

Figure 2. (a) Optical power variation along time and (b) FFT of the optical power variation of the ϕOTDR signal in the position correspondent to the meter inside the tube (590 m) for an applied vibration of 20 Hz.

In order to test the limits of acquisition of the system, the sampling rate was increased to 80 kHz (maximum allowed due to the trigger holdoff of the acquisition system, 12 μs) and the acquisition time reduced to 1 s. Fig. 3 presents the FFT spectra of the optical power variation recorded by the ϕOTDR at the position 590 m when the frequency applied to the tube is raised from 2 kHz to 39.5 kHz. The recorded spectra showed clearly visible peaks in all the applied frequencies, with higher SNR and also higher non-linearity for lower applied frequencies. This corresponds to the fact that, as the frequency is reduced, the tube displacement is larger. For the maximum frequencies tested, the estimated displacement of the tube is in the sub-micron range, which illustrates clearly the extreme sensitivity of this technique. At low frequencies, multiples of 50 Hz are observed below 500 Hz which we believe could be owed to the mechanical actuator. Considering the clearly visible peak at 39.5 kHz, we believe that higher frequencies could still be recorded with higher sampling rates. Furthermore, although measurements were demonstrated in a fiber span of 600 m, considering the previously demonstrated high visibility of the system in longer distances, no problem should be envisaged in extending the monitored fiber span to 1.25 km (limit allowed by the 80 kHz sampling rate), if the trigger hold off of the acquisition system could be reduced. It is worth mentioning that the presented spectra are not averaged or treated in any way, which means that the performance of the sensor could be increased with the proper data treatment for specific applications.

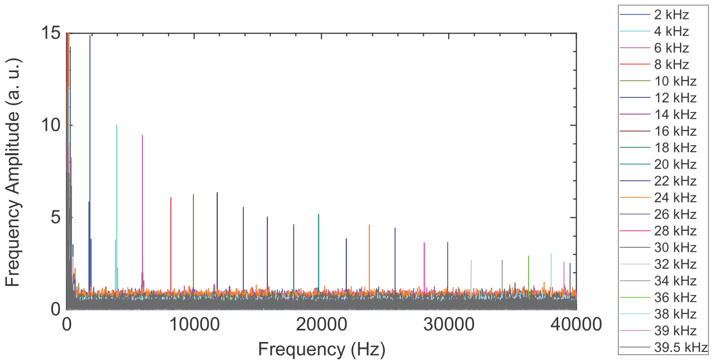

Figure 3. FFT spectra of the optical power variation of the ϕOTDR signal along time in a given meter for an applied vibration from 2 kHz to 38 kHz with intervals of 2 kHz, 39 kHz and 39.5 kHz.

4. CONCLUSION

In this work, the authors present an experimental characterization of a high-visibility ϕOTDR and its performance when used for ultrasonic vibration measurements. The ϕOTDR trace was shown to have high visibility over a minimum of 9.9 km. As for the vibration sensing, the optical power variations of the ϕOTDR trace were shown to be synchronized with applied mechanical vibrations. The sensor was able to measure vibrations of up to 39.5 kHz, limited by the sampling frequency, with a resolution of 5 m in a range which could go up to 1.25 km.

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