Comparison of the use of first and second-order Raman amplification to assist a phase-sensitive optical time domain reflectometer in distributed vibration sensing over 125 km

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ABSTRACT

We report on the use of second-order Raman amplification to assist a phase-sensitive optical time domain reflectometer (ϕOTDR) used for vibration measurements over very long distances. The sensor was able to measure vibrations of up to 380 Hz (limit set by the time of flight of light pulses) in a distance of 125 km with a resolution of 10 m and no post-processing. Balanced detection is used to reduce the relative intensity noise. A comparison with a sensor using first-order Raman amplification under similar conditions is presented and a clear improvement of performance is demonstrated.

Keywords: Distributed sensor, optical fiber sensors, phase-sensitive OTDR, vibration sensor, Raman scattering

1. INTRODUCTION

For more than twenty years phase-sensitive optical time domain reflectometry (ϕOTDR) has been widely studied and reported in the scientific literature [1-5]. ϕOTDR systems attract a great interest due to their potential for fully distributed monitoring of vibrations along an optical fiber cable. This capability has been used for intrusion monitoring over large perimeters [1]. Improved ϕOTDR sensors have been demonstrated to allow the measurement of distributed vibrations of ultrasounds over several hundred meters [2]. Dynamic ranges of a few tens of kilometers with resolutions in the range of meters have also been reported [3]. In ϕOTDR operation, dynamic range, resolution, and signal-to-noise ratio (SNR) are closely related parameters. Although for a given resolution the increase of the ϕOTDR input pump peak power will increase the dynamic range and SNR, this approach is limited due to the onset of nonlinear effects [4]. A significant increase of the dynamic sensing range therefore can only be achieved using optical amplification [5]. A number of different architectures using first and second-order Raman amplification have been proposed to increase the sensing range of distributed fiber sensors [5-7]. In ϕOTDR operation, Raman amplification can be used to maintain the ϕOTDR pump power high along the whole fiber length. Combined with balanced detection to reduce the relative intensity noise (RIN) transfer from the Raman pumps, this approach has been demonstrated to extend the sensing range beyond 100 km [5].

In this paper, the use of second-order Raman amplification to assist a ϕOTDR used for vibration measurements over very long distances is presented, to the best of our knowledge, for the first time. The sensor was able to measure vibrations of up to 380 Hz (limit set by the time of flight of light pulses) in a distance of 125 km with a resolution of 10 m. A comparison with a sensor using first-order Raman amplification under similar conditions is presented. A clear improvement of performance is demonstrated as the ϕOTDR trace presented higher flatness and therefore higher amplitude of oscillations in the lower sensitivity points. The second-order Raman sensor was able to measure vibrations until a higher frequency and with higher SNR in these points. The complexity of the schemes is also kept to a minimum as no post-processing, extremely high coherence lasers or coherent detection methods are required.

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2. EXPERIMENTAL SETUP

The experimental setup used to characterize the ϕOTDR assisted by second-order Raman amplification is shown in figure 1. A laser diode (LD) driven by a standard current and temperature controller with a linewidth of 1.6 MHz emitting at 1548 nm was used as the master source, followed by an optical isolator (ISO). A semiconductor optical amplifier (SOA), with rise/fall times in the order of 2.5 ns and extinction ratio (ER) >50 dB, driven by a waveform signal generator (SG) was used to create 100 ns almost square pulses. An Erbium-Doped Fiber Amplifier (EDFA) was used to boost the power of the ϕOTDR input pulses and reach peak powers of several hundred milliwatts. In order to minimize the effect of the ASE added by the EDFA, we inserted a tunable a tunable filter which presented an approximate gaussian profile with 0.2 nm FWHM. In addition to the tunable filter, an optical switch with rise/fall times of 200 ns and a typical ER of 25 dB was used after the EDFA. It was driven so as to have a sub-microsecond transmission window synchronized with the pulse. This system allows to further increase the ER, reducing the noise delivered into the fiber outside the pulse. After that, light passed through an attenuator, which allowed varying the input pump power in the fiber. The fiber under test (FUT) is connected to the common ports of two WDMs (1310/1550 nm). The input pulse is launched into the FUT through the 1550 nm port of the WDM1. The primary Raman pump is a Raman Fiber Laser (RFL) emitting at 1365 nm with a RIN <-105 dBc/Hz. The power of this laser can be tuned up to 5 W. The RFL beam is divided by a calibrated 50/50 coupler in two beams and each beam is then coupled into the 1310 nm ports of the WDMs. Two FBGs centered at 1455 nm with 0.5 nm FWHM and with 80% reflectivity are placed in both ends of the fiber, thus creating the cavity for the first-order Raman laser. The signal back-reflected from the fiber is amplified (using a micro-EDFA) and then goes through a 100 GHz channel demultiplexer which filters out the channel of the signal (centered at 1547.72 nm) and an adjacent channel (centered at 1548.52 nm), thus filtering out the ASE added by the micro-EDFA. The signal channel and the adjacent channel are then respectively coupled to the “+” and “-” port of a p-i-n balanced photodetector with amplification and 100 MHz bandwidth. These channels are then coupled to the “+” and “-” port of a p-i-n balanced photodetector with amplification and 100 MHz bandwidth. Since the optical paths leading to the “+” and “-” ports are the same, a maximum cancelation of the RIN noise transferred from the Raman pumps is ensured [5]. The signal was then recorded using a high-speed digitizer. As for the experimental setup used to characterize the ϕOTDR assisted by first-order Raman amplification, it is based on a minor adaptation of the setup presented in figure 1, as a first-order Raman pump scheme is used. Also, a fiber Bragg grating (FBG), with a typical spectrum of a 100 % reflection FBG and a spectral width of 0.8 nm working in reflection was used, instead of the 0.2 nm FWHM tunable filter.

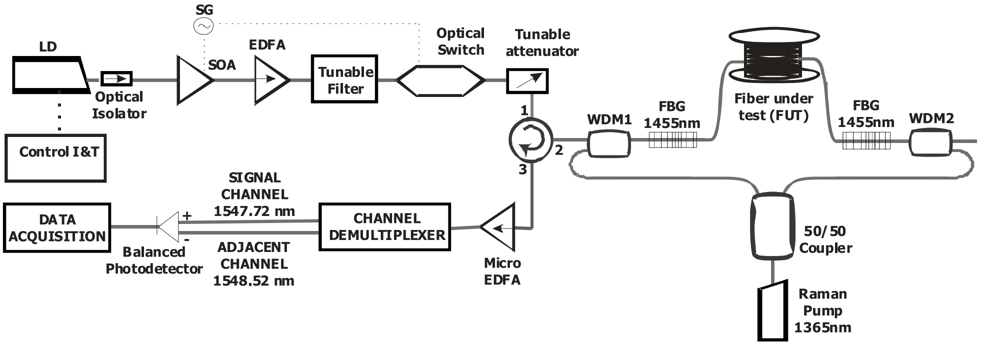

Figure 1. Experimental setup used to characterize the ϕOTDR assisted by second-order Raman amplification. For the first-order Raman amplification a similar scheme with minor adaptations was used. Acronyms are explained in the text.

3. ϕOTDR TRACES

Fig. 2 shows the ϕOTDR traces recorded for the first (Fig. 2a) and second-order (Fig. 2b) Raman assisted ϕOTDRs . The Raman pump power launched on each end of the fiber of 0.6 W and 0.7 W, respectively, and the ϕOTDR pump power was chosen as the one ensuring the best performance in both cases. The evolution of the amplitude of the trace oscillations is as qualitatively expected. Due to a connector loss at ≈98 km (estimated in 3 dB) a decrease of the amplitude of the trace oscillations is observed in that point in both cases. The vibrations were measured immediately after this connector loss, as it was clearly the worse sensitivity point along the fiber. The advantage of using second-order Raman amplification over first-order Raman amplification is clear as the trace presents higher flatness along the fiber under similar measurement conditions. This ensures the best performance as higher amplitude of oscillations and therefore higher SNR is achieved in the lowest sensitivity point. The top figures show the visibility of the ϕOTDR interference signal along the FUT, calculated as indicated in the figure caption. Despite the fact that the amplitude of the oscillations and average reflected power present large variations along the fiber, the variations of the contrast of the interference are much lower (the visibility remains close to 1). Since the visibility of the ϕOTDR trace is not altered along the fiber, we can conclude that reliable vibration measurements can be performed at any position along the fiber if we can ensure sufficient SNR in the position of worst signal level (around km 100 in both cases). Thus, our vibration measurement tests are done in this position.

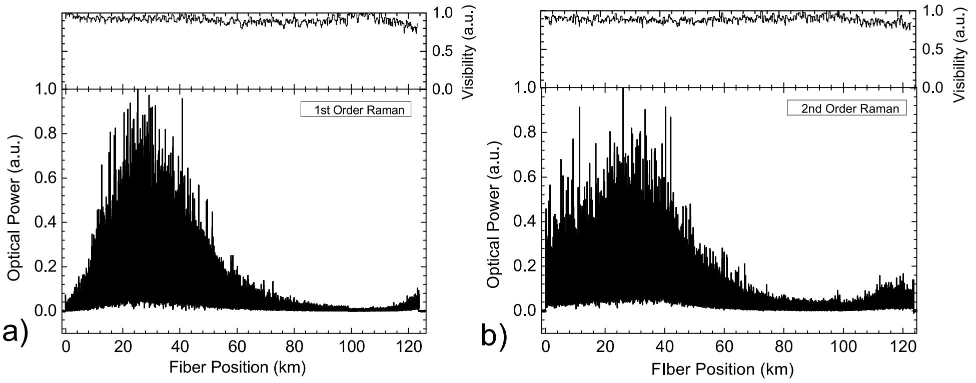

Figure 2. ϕOTDR interference signal along the FUT using (a) first and (b) second-order Raman amplification. The Raman pump power launched on each end of the fiber was 0.6 W and 0.7 W, respectively, and the ϕOTDR pump power was chosen as the one ensuring the best performance in both cases. The top figures show the visibility of the interference signal, 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 500 m.

4. VIBRATION MEASUREMENTS

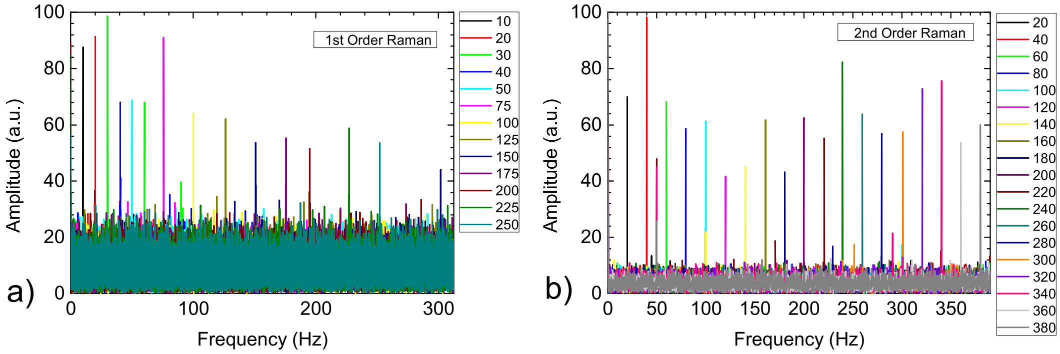

Figure 3. FFT spectra of the optical power variation of the ϕOTDR signal for consecutive traces in the fiber point with minimum amplitude of the trace oscillations (km 98) using (a) first and (b) second-order Raman amplification for applied frequencies between (a) 10 and 250 Hz and (b) 20 and 380 Hz, using the same conditions of fig. 2a and 2b, respectively.

The power evolution as a function of time for each point along the FUT was obtained by monitoring equivalent points in consecutive traces. The FFT of this power evolution will therefore present the frequencies measured for each point. The ϕOTDR pump pulse repetition rate was 625/781 Hz for the first/second-order Raman amplification, which limits the maximum detectable frequency to 312.5/390.5 Hz (Nyquist theorem) and the theoretical maximum fiber span to be monitored to 163/131 km. As for the Raman pump power and input ϕOTDR pump power were the same as the ones used in the traces of figure 2a and 2b. The point with the lowest amplitude of the trace oscillations, which in both cases was observed to be after the connector at ≈98 km, was placed inside a 2 m long PVC tube with 0.08 m of diameter in which mechanical vibrations of controllable frequency 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 variations of the ϕOTDR signal and respective FFTs of fiber points which were more than 10 m away from the PVC tube did not show sensitivity to the applied vibrations. This is in agreement with the expected resolution of 10 m (corresponding to a 100 ns pulse).-Figure 3 presents the FFT spectra of the optical power variations recorded by the ϕOTDR in the position of the PVC tube when frequencies between 10 Hz to 250 Hz using the first-order Raman amplification (Fig. 3a) and 20 Hz to 380 Hz using the second-order Raman amplification (Fig. 3b) were applied to the PVC tube. The recorded spectra showed clearly visible peaks in all the applied frequencies. As expected, when using second-order Raman amplification vibrations were detected until higher frequencies and with higher SNR than when first-order Raman amplification was used. No post-processing was used in the presented data and therefore, to some extent, the performance of the sensor could be increased with the proper data treatment for specific applications.

5. CONCLUSIONS

The use of second-order Raman amplification to assist a phase-sensitive optical time domain reflectometer (ϕOTDR) when used for vibration measurements over very long distances is presented, to the best of our knowledge, for the first time. The sensor was able to measure vibrations of up to 380 Hz (limit set by the time of flight of light pulses) in a distance of 125 km with a resolution of 10 m and no post-processing. A comparison with a sensor using first-order Raman amplification under similar conditions is presented and a clear improvement of performance is demonstrated. These types of sensors can present a very attractive solution to the monitoring of intrusions in large perimeters such as national borders, military bases or pipelines.

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