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Spatial-temporal averaging algorithm for improving vibration detection with low-cost phase-sensitive OTDR

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ABSTRACT

Phase-sensitive optical time-domain reflectometry technique is promising for number of the applications such as perimeter and pipeline security, railway safety and structural health monitoring. The φ-OTDR technique employs the Rayleigh scattering of coherent light pulses in a single-mode optical fiber and delivers detection and localization of the vibrations along sensing fibers of several kilometers. Signal processing algorithm of the φ-OTDR system is looking for changes of the amplitude of the backscattered Rayleigh signal between consecutive traces. Variation of the signal amplitude from pulse to pulse at signal traces is a sign of dynamic perturbations at some positions along the test fiber. Therefore, for proper operation of φ-OTDR systems the optical frequency fluctuations between neighboring pulses should be low enough to maintain the recorded Rayleigh backscattering interference pattern unchangeable as the measurements are applied to an undisturbed fiber. Commonly, a coherent laser source with a few kHz linewidth and frequency drift less than 1 MHz/min is required for long distance measurements. Such lasers are rather expensive and their design appreciably contributes the total cost of the phase OTDR analyzer. Recently, we have proposed a low-cost solution for the phase OTDR technique. It is well known that self-injection locking of a standard telecom DFB laser could significantly improve its spectral purity. In our former works we have demonstrated substantial narrowing of the laser linewidth due to a spectrally selective feedback based on fiber optic ring resonator built from standard telecom components. To implement injection-locking a part of the optical radiation emitted by the DFB laser is passed through the ring resonator and returned back into the laser cavity. This low-cost all-fiber solution enables the laser linewidth as narrow as a few kHz. Here, we report φ-OTDR system based on low-cost telecom DFB laser injection-locked to the PM ring cavity that is naturally free from the polarization mode hopping. In order to minimize other laser instabilities, we have precisely stabilized the current and temperature of DFB laser providing the longest interval for a stable laser operation in injection-locking regime (~7-30 min). Besides, a special spatial-temporal differential averaging algorithm has been applied to the measured φ-OTDR traces, improving ability of the low-cost commercial DFB laser for vibration detection. The use of the proposed algorithm improves the signal-to-peak noise ratio for vibration detection by 3-4 dB. Localization of the vibrations at a frequency of ~815 Hz at a distance ~850 m and the spatial resolution of ~20 m achieved with the injection-locked DFB laser is demonstrated with SNR better than ~13.8 dB.

Keywords: Distributed sensing; phase-OTDR; semiconductor laser; injection locking.

1. INTRODUCTION

Advanced techniques of fiber optic distributed measurements are very promising for a number of applications such as pressure, strain, vibration and temperature measurements employing advanced fiber laser sources in combination with fiber based optical effects [1-28]. Among them are distributed optical fiber sensors, distributed acoustic/vibration sensors (DAS/DVS), which are based on the use of an optical fiber to localize and measure acoustic signals or vibrations along its length, are becoming increasingly attractive for a wide range of applications. These include monitoring oil and gas pipelines, ensuring railway safety and perimeter security, and performing industrial process control. DAS/DVS (distributed

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acoustic / distributed vibration sensors) involve the real-time observation of the properties (amplitude and/or phase) of the Rayleigh backscattered signal in a coherent optical time-domain reflectometer (OTDR) based on a highly coherent laser source, commonly referred to as phase-sensitive OTDR or phase-OTDR (φ-OTDR) [29-34]. A light source providing a few kHz linewidth and frequency drift of less than 1 MHz/min is commonly used with distributed acoustic sensors [31]. Although several designs have been proposed for such master sources, their high cost and complexity may limit potential applications of DAS/DVS in large volume markets. It is well known that self-injection locking of conventional telecom DFB lasers could significantly improve their spectral performance [35-48]. Recently, we have demonstrated that self-injection locking of a conventional DFB laser through an external fiber optic ring cavity causes a drastic decrease in laser linewidth reaching down to 2.4 kHz and makes possible its direct application in a phase-sensitive OTDR system for DAS/DVS sensing [49-63]. Detection and localization of dynamic perturbations to an optical fiber has been demonstrated at the distance of 9270 m [49]. In [56] we have reported on the ability of such a low-cost system to localize perturbations with a similar SNR as a commercial fiber laser based system. The ability of this system to restore the perturbation frequency spectrum has been evaluated in [59,60]. In that work, we have presented SNR results for distributed measurements of the vibration frequency over 4000 m for vibration frequencies in the range of 350-5600 Hz. Specifically, the DFB laser in this work has been stabilized through its locking to an external ring interferometer built from polarization maintaining fiber (PM) components, thus avoiding the polarization mode-hopping that is proved to be a major source of the laser instability [47, 54]. Along with the DFB laser, the same measurements have been performed with the commercial, ultra-narrow-linewidth (~ 100 Hz) fiber laser in the same φ-OTDR setup and under the same experimental conditions. However, the direct comparison of the results has highlighted some limitation of the system performance associated with the use of the low-cost laser configuration.

Here, we introduce a special spatial-temporal differential averaging algorithm that could be applied to the measured φ-OTDR traces in order to improve ability of the low-cost commercial DFB laser for vibration detection. The use of the proposed algorithm increases the signal-to-peak noise ratio for vibration detection by 3-4 dB. Measurements of vibrations at the frequency of ~815 Hz at the distance of ~850 m with the spatial resolution of ~20 m is demonstrated with the low-cost phase-OTDR analyzer comprising the injection-locked DFB laser.

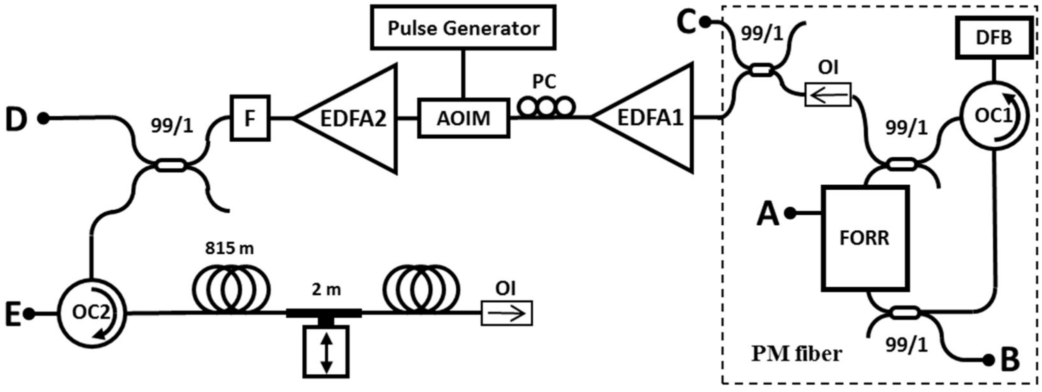

Fig. 1. The experimental configuration of φ-OTDR system with DFB laser locked through FORR. PC – polarization controller, OC- optical circulator, F –optical filter, FORR - fiber optical ring resonator, AOIM - acousto-optic intensity modulator, OI – optical isolator.

2. EXPERIMENTAL CONFIGURATION

The experimental configuration of the phase-OTDR vibration sensor comprising ~4000 m of SMF-28 used as a sensing fiber is shown in Fig.1. The master laser is a conventional low-cost DFB laser commonly employed for telecom applications. The free-running DFB laser operates at 1548.5 nm with an output power of ~7.4 mW and a linewidth of ~1 MHz. For linewidth narrowing and frequency self-stabilization, the laser is sliced with the 3.75 m polarization maintaining (PM) optical fiber ring resonator. The use of PM fiber components prevents the polarization mode-hopping that is proved to be a major source of the laser instability [47], resulting in single frequency laser operation with 6 kHz linewidth. The laser diode current of 50 mA (the threshold current is 10 mA) and the operation temperature of 25 ºC, both stabilized with accuracies better than 0.3%, have been experimentally adjusted to achieve the best laser performance [54]. All laser components are placed into a special insulating box to protect the laser from external perturbations. Under these conditions, the laser long-term frequency drift is mainly determined by the thermal stability of the external ring cavity and estimated to be less than ~30 MHz/min. The duration of laser operation in self-maintaining stabilization regime is up to ~30 minutes.

The tested fiber is interrogated by rectangular pulses with ~100 mW of peak power and ~100 ns duration providing a sensor spatial resolution of ~10 m. The pulses with the repetition rate f0 of 20.3 kHz are produced from a narrow-band master laser modulated by an acousto-optic modulator and amplified by EDFAs. A 2 GHz bandpass filter (BPF) is used to reduce the ASE noise. The fiber is subject to vibrations produced by a shaker connected to a plastic tube onto which 2 m of the fiber is attached at the position 850 m. The results reported on here consider the shaker producing sinusoidal vibrations at frequencies of 815 Hz.

2. MASTER LASER PERFORMANCE

Figure 2 shows typical oscilloscope traces recorded at ports B (transmitted power) and A (reflected power) from the master self-injection-locked laser operating in the critical coupling regime. A stable single frequency laser operation is observed during some time intervals, which are interrupted by short-time mode hopping events. The frequency drift during the stable operation periods strongly depends on environmental conditions and is commonly less than 10 MHz/min. To achieve these conditions the FORR and the laser diode both are placed inside the foam plastic box for thermal fluctuation and environmental noise protection.

The delayed self-heterodyne spectra of the master laser recorded with the unbalanced Mach-Zehnder interferometer comprising 110 MHz phase modulator and 25 km delay fiber length for the stable and free running laser operation are shown in Fig. 3 a) and b), respectively. One can see that the laser operation linewidth Δν of the free running DFB laser decreases from approximately 1 MHz to 6 kHz when the DFB laser is locked to the FORR. The linewidth narrowing is reflected in the port A power level (see Fig. 2). The lower power level recorded at port A the more power is travelling inside the FORR and more transmitted power is available for the DFB feedback through OC1. Correspondingly, the level of the transmitted power (port B) shown in Fig. 2 displays the quality of self-injection locking of DFB laser. For unlocked laser all input power goes at port A and the level of the transmitted power (port B) gets its minimum. For perfectly locked laser all power goes inside the FORR and the level of the transmitted power level (port B) is maximal [63]. Importantly, the recorded laser linewidth Δν is directly correlated with the transmitted power level. As it is shown in Fig.4, higher transmitted power level corresponds to narrower laser linewidth and versa.

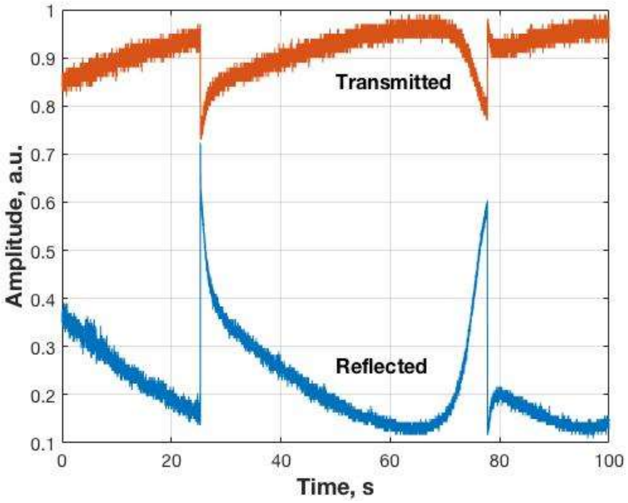

Fig. 2. Typical oscilloscope traces for transmitted and reflected powers at critical coupling regime.

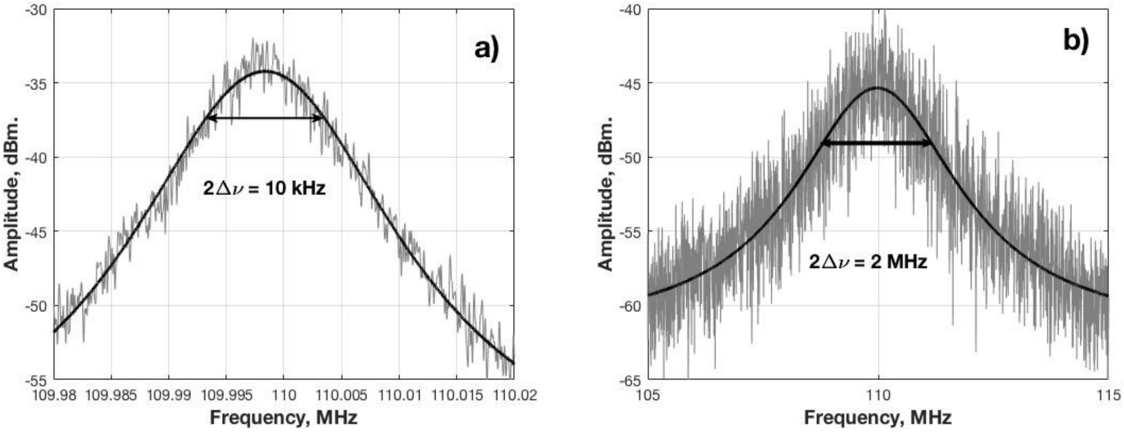

Fig. 3. Delayed self-heterodyne spectra of the laser for stable interval: a) injection-locked laser, b) free running DFB laser.

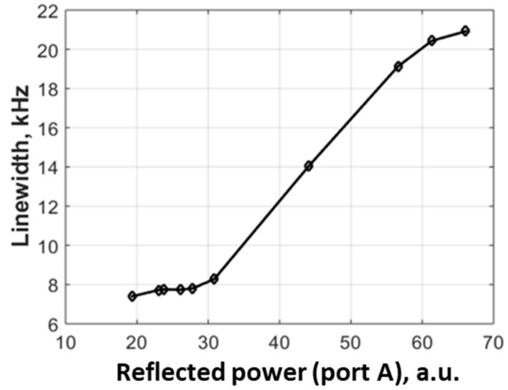

Fig. 4. The master laser linewidth as a function of the reflected power monitored through the port A.

3. SIGNAL PROCESSING ALGORITHM AND ITS EFFECT ON SIGNAL-TO-NOISE RATIO

During the experiments, each probe pulse launched into the sensing fiber generates a backscattered signal that is recorded with a fast photodetector by a 200 MS/s digitizer. A raw trace consists of M = 8000 points, which corresponds to a fiber length L0 of 4 km, i.e. the sampling resolution is ~0.5 m. For signal processing we use N = 932 consecutively recorded raw traces forming the signal $N \times M$ matrix $\{s_{nm}\}$. Each matrix element s_{nm} is averaged over the nearest row elements, i.e. in the spatial domain: $\tilde{s}_{nm} = \frac{1}{w} \sum_{k=m-(w-1)/2}^{m+(w-1)/2} s_{nk}$, where w is a averaging window size, and distance point m is inside the interval: $(w-1)/2 < m < M - (w-1)/2$. This procedure smooths the recorded traces and filters out signal noise behind the spectral band corresponding to the averaging window w . In particular, $w = 21$ corresponds to ~10 m of the spatial resolution.

Following the standard procedure, we can generate the output alarm signal $U(m) = \sum_{n=1...931} |\tilde{s}_{n+1m} - \tilde{s}_{nm}|$ characterizing the effect of vibration in each locale fiber point m . Fig. 5 shows the normalized signal obtained with $w = 21$ for the case of vibration at 815 Hz applied to the fiber point $m = m_v$ corresponding to $\sim 850m$. One can see that the signal obtained from the vibration point m_v exceeds the highest noise level in ~ 1.4 times.

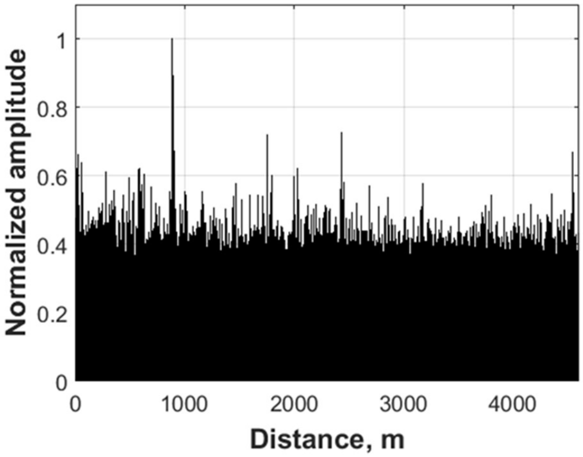

Fig. 5. The standard sensor alarm signal $U(m)$ at $w = 21$, obtained for the case of the vibration at 815 Hz applied to the fiber point ~ 850 m.

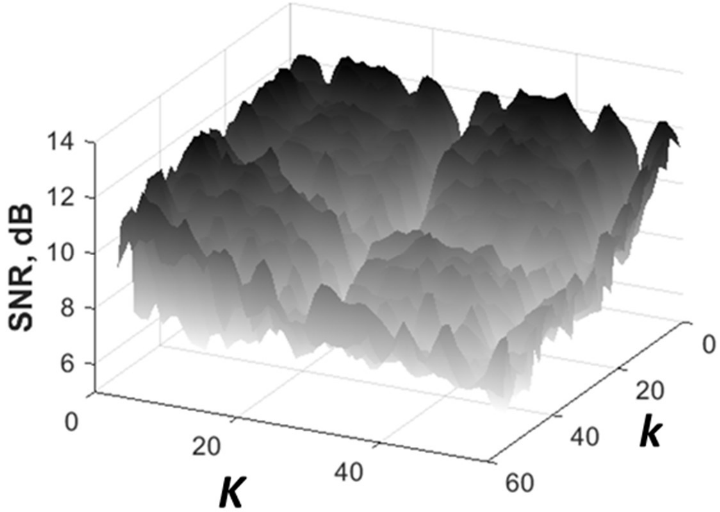

Fig. 6. The signal-to-noise ratio SNR_k at $w = 21$ as a function of the algorithm parameters K and k, obtained for the case of the vibration at 815 Hz applied to the fiber point ~ 850 m.

In order to improve the SNR the following advanced procedure has been applied to the matrix $\{\tilde{s}_{nm}\}$, now, to the time domain, i.e. keeping the coordinate point m fixed. First, we calculate the partial sum $S_{j,k}(m) = \frac{1}{K}\sum_{n=1+k(j-1)}^{i=K+k(j-1)} \tilde{s}_{nm}$, where $k \geq 1$ and $j = 1...(932-K)/k$. Then we evaluate the differences between the consecutive partial sums $D_{j,k}(m) = \left|S_{j+1,k}(m) - S_{j,k}(m)\right|$. And finally, the positive value $G_k(m) = \sum_j D_{j,k}(m)$ is used as the sensor alarm signal.

The result of the alarm signal reconstruction depends on the parameters K and k. The signal/noise ratio is determined as a ratio between the alarm signal recorded at the point of vibration m_v and the average signal recorded in all fiber points:

$$SNR_k = 10\lg\frac{G_k(m_v)}{\langle G_k(m), m\rangle}$$

The dependence of the SNR_k on two algorithm parameters K and k calculated with $w = 21$ for the case of the vibration at 815 Hz applied to the fiber point ~ 850 m is shown in Fig. 6. One can see that the maximal SNR_k of 12.9 dB is achieved with K = 5 and k = 12. The optimal SNR_k depends on the selected window size w as well, i.e. on the spatial resolution. One can see from Fig.7 that the maximal SNR of 13.8 dB is achieved with $w = 9$ corresponding to ~5m of the spatial resolution. It allows to improve SNR by ~1 dB in comparison with the case of $w = 21$.

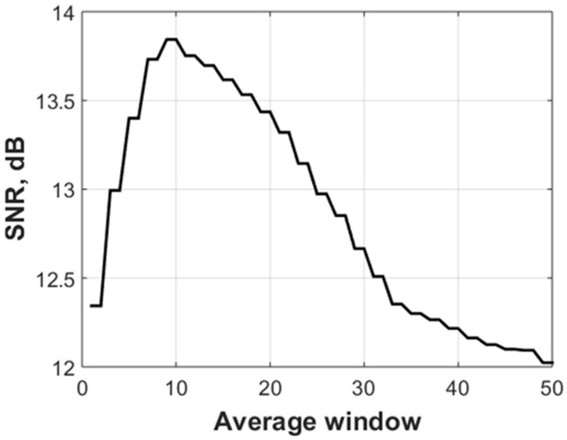

Fig. 7. The signal-to-noise ratio SNR_k with the optimal algorithm parameters K and k as a function of the average window w, obtained for the case of the vibration at 815 Hz applied to the fiber point ~ 850 m.

Figure 8 shows the normalized signal $G_k(m)$ calculated with the optimal values of K, k and w that reflects the vibration at 815 Hz applied to the fiber point ~ 850 m. One can see that the alarm signal in Fig.8 exceeds the highest noise peak in ~ 2.5 times, i.e. provides ~1.5 times better detection ability than the standard alarm signal shown in Fig.4.

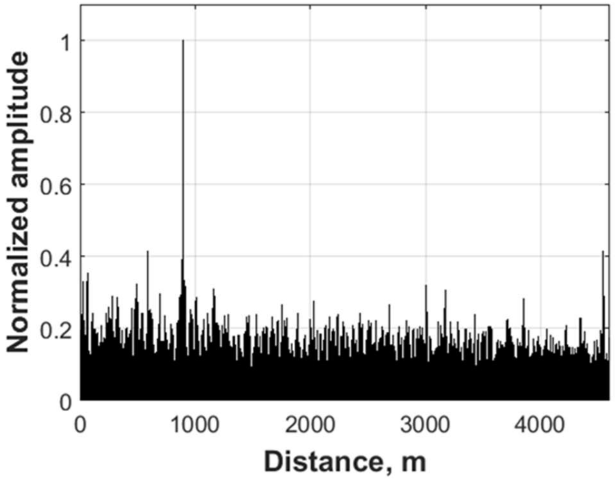

Fig. 8. The sensor alarm signal $G_k(m)$ with the optimal algorithm parameters K, k and w, obtained for the case of the vibration at 815 Hz applied to the fiber point ~ 850 m.

4. CONCLUSION

We have reported φ-OTDR system based on low-cost telecom DFB laser injection-locked to the PM ring cavity that is naturally free from the polarization mode hopping. In order to minimize other laser instabilities, we have precisely stabilized the current and temperature of DFB laser providing the longest interval for a stable laser operation in injection-locking regime (~7-30 min). A special spatial-temporal differential averaging algorithm has been applied to the measured φ-OTDR traces, improving ability of the low-cost commercial DFB laser for vibration detection. The use of the proposed algorithm improves the signal-to-peak noise ratio for vibration detection by 3-4 dB. Localization of the vibrations at a frequency of ~815 Hz at a distance ~850 m and the spatial resolution of ~20 m achieved with the injection-locked DFB laser is demonstrated with SNR better than ~13.8 dB. We believe that the proposed solution can be useful for design of cost-effective φ-OTDR systems enabling measurements of perturbations at distances up to tens of kilometers. The use of special metal-coated and FBG array fibers [19-24] in combination with the injection-locked DFB laser diode based φ-OTDR configuration and supported by the advanced signal processing algorithm will bring new advance in distributed acoustic sensing in terms of the cost efficiency, signal-noise ratio, sensitivity.

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