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Distributed measurements of vibration frequency using phase-OTDR with a DFB laser self-stabilized through PM fiber ring cavity

J.L. Bueno Escobedo[a,c], J. Jason[b], C.A. López-Mercado[b,c], V.V. Spirin[c,*], M. Wuilpart[b], P. Mégret[b], D.A. Korobko[d], I.O. Zolotovskiy[d], A.A. Fotiadi[b,d,e,f]

[a] Centro de Investigación en Materiales Avanzados, (CIMAV), Ave. Miguel de Cervantes No. 120, Complejo Industrial Chihuahua, C.P. 31109 Chihuahua, Mexico
[b] University of Mons, Boulevard Dolez 31, 7000 Mons, Belgium
[c] Scientific Research and Advanced Studies Center of Ensenada (CICESE), Carretera Ensenada-Tijuana No. 3918, Zona Playitas, 22860 Ensenada, B.C., Mexico
[d] Ulyanovsk State University, 42 Leo Tolstoy Street, Ulyanovsk 432970, Russia
[e] School of Engineering and Applied Science, Aston University, Birmingham B4 7ET, UK
[f] Ioffe Physico-Technical Institute of the RAS, 26 Polytekhnicheskaya Street, St. Petersburg 194021, Russia

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ABSTRACT

We have evaluated the performance of a phase-sensitive optical time domain reflectometry (φ-OTDR) system for vibration measurements utilizing a conventional telecom DFB laser self-stabilized through an external PM optical fiber ring resonator. This low-cost solution is directly compared with the use of a commercial, ultra-narrow linewidth (~100 Hz) fiber laser implemented into the same setup. Both systems are tested for measurement of the frequency of vibration applied to a fiber at a distance of 3500 m. The obtained SNR value higher than 6 dB demonstrates the ability of the DFB laser to perform distributed measurements of vibrations with frequencies up to 5600 Hz with a spatial resolution of 10 m.

For the last decade, phase-sensitive optical time domain reflectometry systems employing Rayleigh backscattering in a sensing fiber have been extensively studied for a variety of applications such as monitoring of oil and gas pipelines, railway safety and perimeter security [1,2]. Light sources providing a few kHz linewidth and a frequency drift of less than 1 MHz/min are commonly used with such sensor systems [2]. Their high cost and complexity hinder potential applications of the Rayleigh sensors in a large volume market. 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 [3–5] and makes possible its direct application in a phase sensitive OTDR system [6]. In that work, the DFB laser was partially stabilized with an optical fiber ring resonator built from a standard (non-PM) SMF-28 fiber. For the laser stabilization in [7] we utilized an optical PM fiber ring resonator thus preventing polarization instabilities [5]. A self-maintaining stable laser operation interrupted by mode-hopping events was observed during 1–100 s. In that work, we evaluated the ability of a low-cost system to localize perturbations with a similar SNR as the commercial laser based system. However, the laser instabilities interfered reliable and repeatable measurements of the perturbation spectra. In this paper, with precise stabilization of the laser configuration temperature and the laser diode current, we have extended the duration of laser operation in self-maintaining stabilization regime to ~30 min. We present results of new experiments evaluating the SNR for distributed measurements of the vibration spectrum over 4000 m for vibration frequencies in the range of 350–5600 Hz. Along with the DFB laser, the same measurements have been performed with the use of the commercial, ultra-narrow-linewidth (~100 Hz) fiber laser with the same φ-OTDR setup and under the same experimental conditions. The direct comparison of the results highlights no limitation of the system performance associated with replacement of the commercial fiber laser by the low-cost laser.

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 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 f_0 of 20.3 kHz are produced from a narrow-band master laser modulated by an acousto-optic modulator and amplified by an EDFA. A 2 GHz bandpass filter (BPF) is used to reduce the ASE noise. The fiber is subject to two perturbations: dynamic strain produced by a piezo-electric fiber stretcher working over 40 m of fiber at the position 1800 m, and vibration produced by a shaker connected to a plastic tube onto which 2 m of the fiber is attached at the position 3500 m. The results reported on here consider the

* Corresponding author.
E-mail address: vaspir@cicese.mx (V.V. Spirin).

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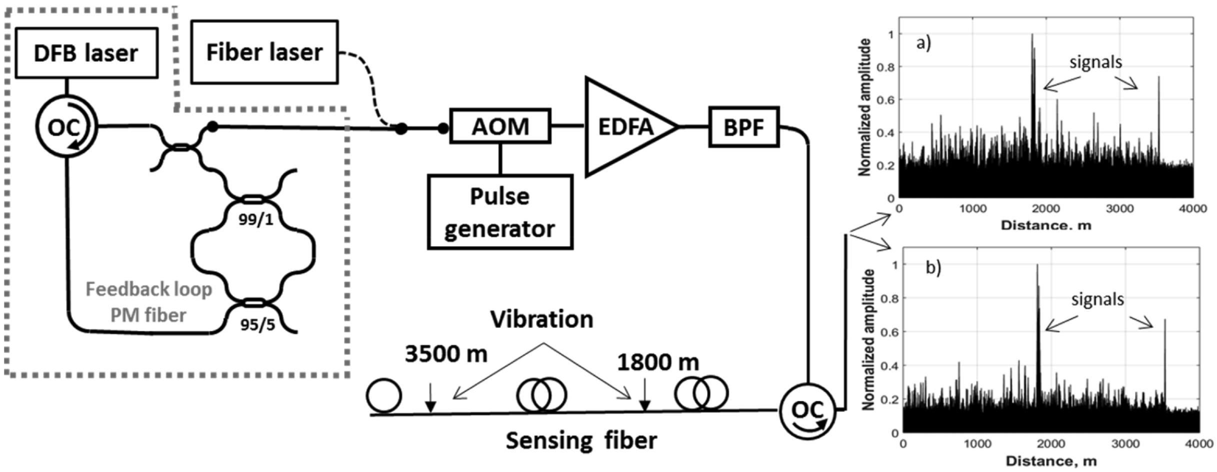

Fig. 1. Experimental setup and examples of difference traces enabling localization of the perturbation points, obtained with the low-cost DFB laser (a) and the commercial fiber laser (b).

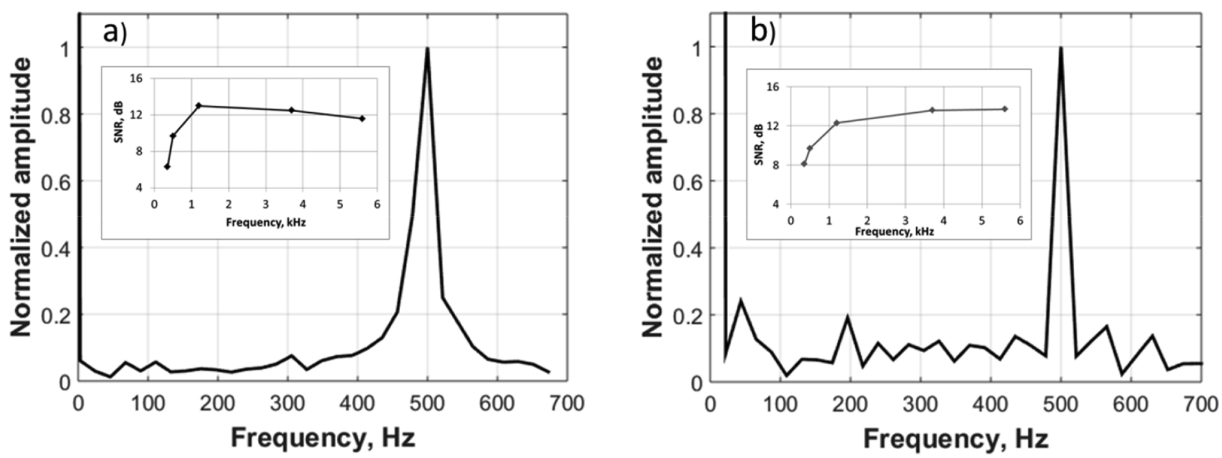

Fig. 2. Vibration frequency spectrum recorded at ~3500 m with the low-cost DFB laser (a) and commercial fiber laser (b). Inserts show SNR as a function of the frequency.

shaker perturbation at 3500 m, producing sinusoidal vibrations at frequencies of 350, 500, 1200, 3700 and 5600 Hz.

Two different laser sources have been used as a master laser with the experimental setup. The first 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 [5], 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 °C, both stabilized with accuracies better than 0.3%, have been experimentally adjusted to achieve the best laser performance theoretically predicted in [8]. 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. In comparison with [7], the duration of laser operation in self-maintaining stabilization regime has been extended to ~30 min. The second laser used in the experiment as an etalon master source is a commercial fiber laser operating at 1552.5 nm with an output power of ~40 mW and a linewidth of ~100 Hz. According to the specification, the laser exhibits a frequency drift of roughly 1 MHz/min.

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 L_o 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 $\{s_{nm}\}$. Following [1] each matrix element s_{nm} is averaged over the 20 nearest row elements, i.e. in the spatial domain: $\widetilde{s}_{nm} = \frac{1}{w}\sum_{k=m-(w-1)/2}^{m+(w-1)/2} s_{nk}$ with $w = 21$. This procedure smooths the recorded traces and filters out signal noise behind the spectral band corresponding to the ~10 m spatial resolution. Further signal processing is applied to the matrix $\{\widetilde{s}_{nm}\}$, this time along the matrix columns (in the time domain): the use of the moving differential algorithm [6,7] results in the signal shown in Fig. 1, exhibiting pronounced peaks at the positions of the applied perturbations.

The spectral function $U(f_k, x_m) = FFT(\widetilde{s}_{nm}, m, k)$ of frequencies $f_k = f_0(k-1)/(N-1)$ describes the spectrum of the vibrations at the fiber position $x_m = L_0(m-1)/(M-1)$. It is obtained from $\{\widetilde{s}_{nm}\}$ by a fast Fourier transform (FFT). Fig. 2 shows the spectrum $U(f_k, x_m)$ recorded for a vibration frequency of ~500 Hz at the position $x_m \sim 3500$ m obtained with the low-cost and the commercial laser, respectively. For the configuration with the DFB laser (a) the spectrum peak exceeds the highest noise level about ~10 times providing proper recognition of the applied vibration frequency. SNR defined as the ratio between the spectrum peak and the RMS spectral noise level is estimated to be ~9.4 dB. For the configuration with the commercial laser (b) these values are nearly the same, ~9 times and 9.0 dB, respectively. The dependency of the SNR on the vibration frequency is shown in the insets to Fig. 2. To account for differences in the response [9] between each measurement (causing stochastic fluctuations of the peak widths and background), several (5–10) measurements were made for each frequency and the SNR values presented represent the average in each case. One can see that SNR smoothly increases with an increase of the vibration frequency. It could be explained by the narrowing of the spectrum peak recovered through FFT following an increase of the number of vibration periods accounted for the fixed time of measurements. At low vibration frequencies, both configurations possess similar SNR. For higher frequencies, slightly lower SNRs are obtained with the low-cost laser due to its faster frequency drift, and the difference in SNR is about 10% at a vibration frequency of 5600 Hz. In the latter case, the frequency f_0 is only 3.6 times the measured frequency, however, sufficient number of interrogation cycles $N = 932$ provides reliable reconstruction of the vibration peak from the matrix $\tilde{s}_{nm}$. The SNR value exceeds 8 dB for all vibration frequencies ≥ 500 Hz.

In summary, we have studied the capacity of a conventional telecom DFB laser to operate as an interrogating master source in phase-OTDR-based vibration sensor system. For operation in a stable single frequency mode, the DFB laser has been injection-locked with an external fiber interferometer spliced from standard PM fiber components. The obtained SNR values confirm the ability of the proposed technique to perform distributed measurement of vibration frequencies with a spatial resolution of 10 m. We believe that new low-cost and simple solution will extend the range of potential Rayleigh sensor applications making them available for a large volume market.

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