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Cost-effective solution for phase-OTDR distributed acoustic/vibration sensing

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ABSTRACT

Self-injection locking - an efficient method to improve the spectral performance of semiconductor lasers without active stabilization - has already demonstrated its high potential for operation with single-longitude-mode fiber lasers. Recently, we demonstrated that self-injection locking of a conventional DFB laser through an external fiber optic ring cavity causes a drastic decrease of the laser linewidth and makes possible its direct application in a phase-sensitive optical time domain reflectometry (φ-OTDR) acoustic sensor system. Detection and localization of dynamic perturbations in the optical fiber were successfully demonstrated at the distance of 9270 m. However, the ability of the system to restore the perturbating frequency spectrum was not quantified. Here, we have evaluated the performance of a φ-OTDR system for acoustic/vibration measurements utilizing a conventional telecom DFB laser self-stabilized through an external 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, resulting in single frequency laser operation with 6 kHz linewidth. The laser diode current and the laser fiber configuration temperature both have been stabilized with accuracies better than 0.3%. All laser components have been placed into a special insulating box to protect the laser from external perturbations. Under these conditions, the typical duration of laser operation in self-maintaining stabilization regime is ~30 minutes. The laser long-term frequency drift is estimated to be less than ~30 MHz/min. 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 be used in distributed measurements of vibrations with frequencies up to 5600 Hz with a spatial resolution of 10 meters.

Keywords: Phase-sensitive OTDR; optical fiber ring resonator; self-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 [1-18]. Among 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 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) [19-22]. A light source providing a few kHz linewidth and frequency drift of less than 1 MHz/min is commonly used with distributed acoustic sensors [19]. Although several designs have been proposed for such master sources, their high cost and complexity may limit potential

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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 [23-34]. 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 [35-45] and makes possible its direct application in a phase-sensitive OTDR system. Detection and localization of dynamic perturbations to an optical fiber has been demonstrated at the distance of 9270 m [38]. In [45] 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. However, the ability of this system to restore the perturbation frequency spectrum has not yet been evaluated. In this paper, we present 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 (PM) fiber components, thus avoiding the polarization mode-hopping that is proved to be a major source of the laser instability [43]. 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. The direct comparison of the results highlights some limitation of the system performance associated with the use of the low-cost laser configuration.

2. EXPERIMENTAL RESULTS AND ANALYSIS

Figure 1 shows the experimental configuration of the phase-OTDR vibration sensor. A ~4000 m length of SMF-28 is used as sensing fiber. The sensing fiber is interrogated by rectangular pulses with ~100 ns duration. The sensor spatial resolution determined by the pulse duration is ~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 (AOM). Then the pulses are amplified by an EDFA to ~100 mW of peak power. 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 of 2 m length. The fiber is glued along the length of the tube at the position of 3500 m. The results reported on here consider the shaker perturbation, producing sinusoidal vibrations at frequencies of 350, 500, 1200, 3700 and 5600 Hz.

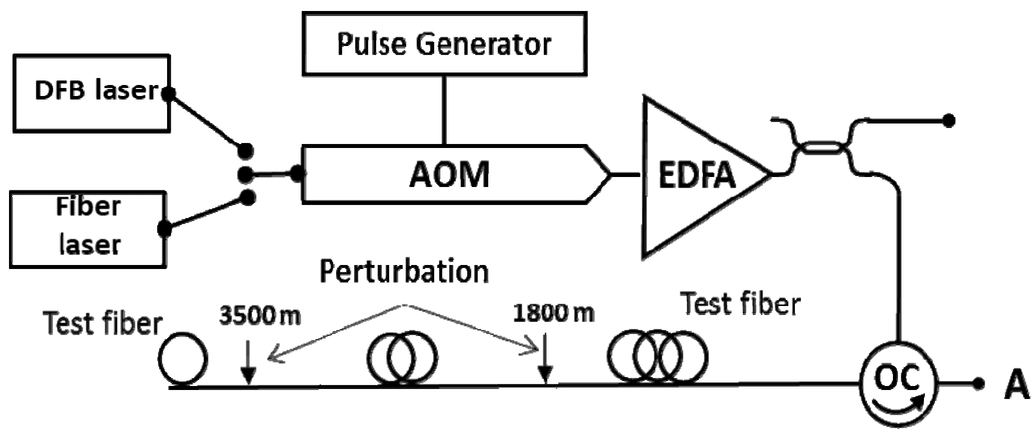

Figure 1. Setup for detection of the vibration in the test fiber, OC- optical circulator, AOM - acousto-optic modulator, DFB laser - self-injection locked DFB laser, Fiber laser - commercial low noise fiber laser, A - detection unit (photodiode, PC-controlled digitizer)

Two different laser sources have been used as master laser in the experimental setup. The first is a conventional low-cost DFB laser (QDFBLD-1550-50, QPhotonics) commonly employed for telecom applications. The free-running DFB laser emits ~7.4 mW at 1548.5 nm with a linewidth of ~1 MHz. In order to achieve linewidth narrowing and stable operation the following arrangements have been made:

a) For linewidth narrowing and frequency self-stabilization the DFB laser is sliced with the 3.75-m PM optical fiber ring resonator. The use of a PM fiber spliced configuration allows to eliminate the polarization mode hopping [36].
b) The parameters of the feedback loop have been adjusted for the best laser performance. Note that the dynamical behavior of the DFB laser injection-locked to the PM fiber interferometer is described by the model in [43].

According to the model, laser linewidth narrowing to sub-kHz range could be achieved with a feedback strength estimated to - 40dB. However, a factory built-in optical isolator in the DFB laser component takes already -30 dB from this total budget. Consequently, we were not able to achieve the optimal feedback value, resulting in single frequency laser operation with 6 kHz linewidth.

c) The model presented in [43] predicts a self-stabilized laser operation in single frequency mode under conditions of strong thermal and current stabilization. The laser operational conditions - the laser diode current of 50 mA (threshold current being 10 mA) and the operation temperature of 25 ºC - have been determined experimentally to achieve the best laser performance. Both parameters were stabilized with accuracies better than 0.3%.
d) The temperature stabilization better than 0.3% has been applied also to the external optical fiber cavity.
e) All laser components are placed into a special insulating box to protect the laser configuration from external perturbation.

Under these conditions the laser frequency drift, mainly determined by the thermal stability of the external ring cavity, is estimated to be less than ~20-30 MHz/min. The typical duration of laser operation in self-supporting stabilization regime is ~30 minutes.

The second laser used in the experiment as an etalon master source is a NKT Koheras AdjustiK (E15 model) low noise fiber laser emitting ~40 mW at ~1552.5 nm with a linewidth of ~100 Hz. According to the specification, the laser exhibits a frequency drift of roughly 1 MHz/min.
In order to have equal output power for both laser sources used in the experiment, an additional EDFA was used after the self-injection locked DFB-laser (IL-DFB laser) to boost its output.

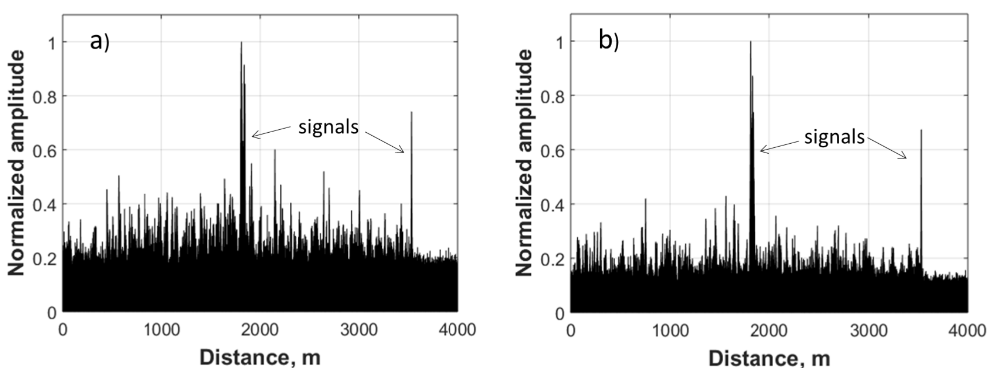

Figure 2. Resulting traces obtained using a) injection locked DFB laser, b) commercial fiber laser. Perturbations are applied at 1800 m and 3500 m.

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 $\{s_{nm}\}$. Each matrix element s_{nm} is averaged over the 20 nearest row elements, i.e. in the spatial domain: $\tilde{s}_{nm} = \frac{1}{w} \sum_{k=m-(w-1)/2}^{m+(w-1)/2} s_{nk}$ 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 $\{\tilde{s}_{nm}\}$, this time along the matrix columns (in the time domain), by applying the moving differential algorithm
[38, 45] to the matrix $\{\tilde{s}_{nm}\}$. This results in difference trace signals typically as shown in Figure 2. The difference signal exhibits pronounced peaks at the positions of the applied perturbations and ensures proper determination of the vibration points. Figure 2 (a) and (b) show the signals obtained with the low-cost and commercial lasers, respectively, applying ~3000 Hz perturbations at both locations. In both cases the pronounced signal peaks can be identified at the positions of ~1800 m and~3500 m. For the configuration with the DFB laser the recorded peak values exceed the highest noise signal

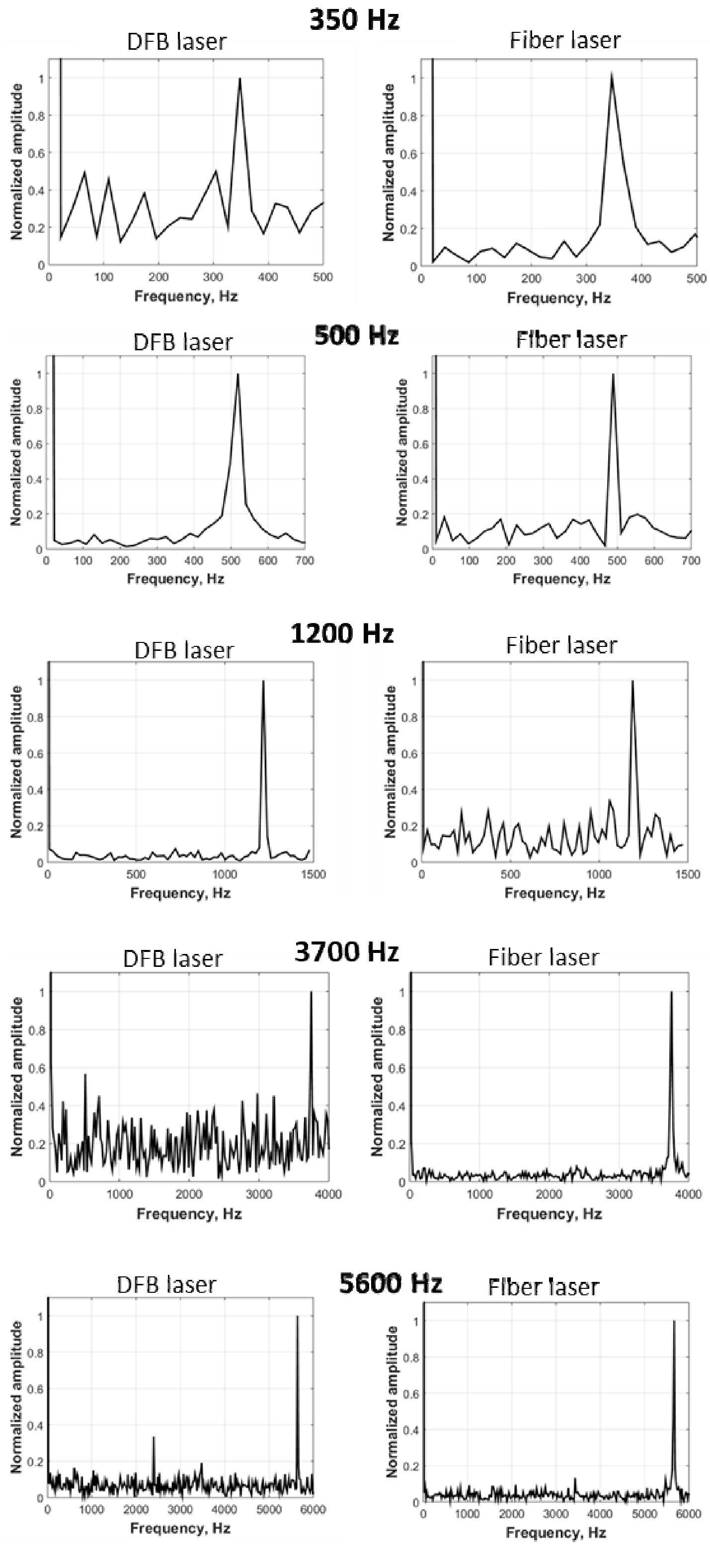

Figure 3. Vibration frequency spectra recorded at ~3500 m with the low-cost injection locked DFB laser (left) and with the commercial fiber laser (right).

about 2.4 times. SNR evaluated as a ratio between the signal peak value and RMS noise level is ~14.5 dB. For the configuration with the commercial laser these values, being 2.9 times and 15.6 dB, respectively, are not very different.

The spectral function $U\left(f_k, x_m\right) = FFT\left(\tilde{s}_{nm}, m, k\right)$ of frequencies $f_k = f_0\left(k-1\right)/\left(N-1\right)$ describes the spectrum of the vibrations at the fiber position $x_m = L_0\left(m-1\right)/\left(M-1\right)$. It is obtained through a fast Fourier transform (FFT) applied to matrix $\left\{\tilde{s}_{nm}\right\}$. Fig. 3 shows examples of the spectra $U\left(f_k, x_m\right)$ recorded for the vibration frequencies of 350, 500, 1200, 3700 and 5600 Hz at the position $x_m \sim 3500m$ obtained with the low-cost and the commercial laser, respectively. For the vibration frequency of 500 Hz, the configuration with the DFB laser (left) gives a spectrum peak that 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 in this case. For the configuration with the commercial laser (right) at the same vibration frequency, these values are nearly the same, ~9 times and 9.0 dB, respectively. For the other vibration frequencies the recovered spectra demonstrate similar features.

The dependency of the SNR on the vibration frequency is shown in Figure 4. To account for differences in the response between each measurement, several (5-10) measurements were made for each frequency and the SNR values given represents the average in each case. One can see that SNR smoothly increases with an increase of the vibration frequency. It could be explaned 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 measurement. 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. The SNR value however exceeds 8 dB for all vibration frequencies > 500 Hz.

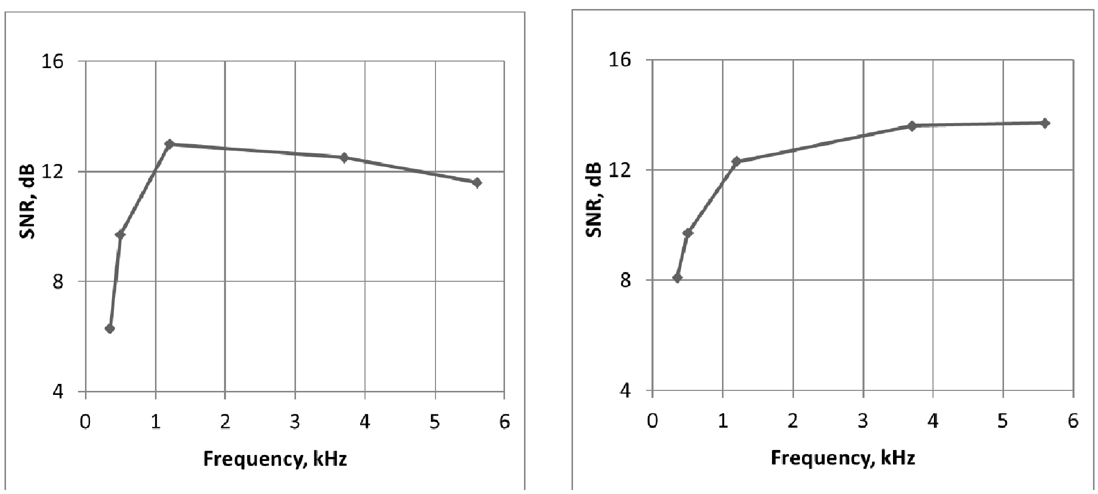

Figure 4. SNR for the frequency determination as a function of the vibration frequency in the case of the low-cost, injection locked DFB laser (left) and the commercial fiber laser (right).

3. CONCLUSION

In summary, we have studied the capacity of a conventional telecom DFB laser to operate as an interrogating master source in a 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, resulting in a linewidth of 6 kHz. The obtained SNR values confirm the ability of the proposed technique to perform distributed measurement of vibration frequencies with a spatial resolution of 10 meters. We believe that the proposed solution can be useful for applications in a cost-effective phase-OTDR system for vibration frequency measurements at distances up to ten kilometers.

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