ISSN 0020-4412, Instruments and Experimental Techniques, 2020, Vol. 63, No. 4, pp. 476–480. © Pleiades Publishing, Ltd., 2020.
Russian Text © The Author(s), 2020, published in Pribory i Tekhnika Eksperimenta, 2020, No. 4, pp. 40–44.

GENERAL EXPERIMENTAL TECHNIQUE

Using a Semiconductor Laser with Frequency Capture as an Operating Optical Generator of a Coherent Reflectometer for Distributed Vibration Frequency Measurements[1]

V. V. Spirin[a], C. A. López-Mercado[a], M. Wuilpart[b], D. A. Korobko[c],
I. O. Zolotovsky[c], and A. A. Fotiadi[b,c,d,*]
[a] *CICESE Research Center, Ensenada, 22860 Mexico*
[b] *Université de Mons, Place du Parc 20, 7000 Mons, Belgium*
[c] *Ulyanovsk State University, Ulyanovsk, 432970 Russia*
[d] *Ioffe Institute, Russian Academy of Sciences, St. Petersburg, 194021 Russia*
**e-mail: fotiadi@mail.ru*

Received March 8, 2020; revised March 19, 2020; accepted March 20, 2020

Abstract—A standard distributed feedback semiconductor laser that is self-stabilized through the frequency capture effect of an external fiber ring resonator is able to replace the standard reference oscillator of a coherent reflectometer in the system of a distributed fiber vibration sensor. A direct comparison of the signal-to-noise ratio, as measured in configurations with a semiconductor and reference master oscillator, has been carried out for quantitative assessment of the ability of the system to restore the frequency spectrum of vibrations. Distributed measurements of vibration spectra with frequencies up to 5600 Hz and a spatial resolution of 10 m when performed on an optical fiber at a distance of ~3500 m show a signal-to-noise ratio above ~8 dB for both configurations. The difference between the configurations was less than 2 dB over the entire spectral range.

DOI: 10.1134/S002044122005005X

In the last decade, optical coherent reflectometry systems have been actively developed that are specialized for applications in acoustic monitoring systems, such as the protection of special facilities, oil and gas pipelines, and railway tracks. [1–3]. Based on the effects of Rayleigh backscattering in optical fibers, such a system uses a stabilized high coherence laser emitter as the master oscillator, providing a generation line width of several kilohertz and a frequency drift of less than ~10 MHz/min [4, 5].

Standard distributed feedback semiconductor lasers do not meet the necessary coherence requirements, since the typical width of their generation line is several megahertz. However, the spectral characteristics of a semiconductor laser can be significantly improved in the optical configuration, which provides the capture of the frequency of the external fiber cavity by the laser [6–10]. In this case, the width of the generation line of a semiconductor laser can be narrowed by several orders of magnitude (up to several kilohertz), and the stability of the generation frequency in the frequency capture mode is determined by the stability of the resonant frequency of the external resonator.

This effect opens up prospects for creating affordable coherent reflectometers for a wide class of new applications [11, 12]. In an experiment [13] we evaluated the ability of a coherent reflectometer based on a semiconductor laser with frequency capture to detect and locate acoustic disturbances in a 4.5-km test fiber line. It was shown that the efficiency (signal-to-noise ratio) of detecting a vibration source and the accuracy of its localization in this case are no worse than in the case of using an expensive standard driver.

This article presents the results of new experiments [14] to study the features of using a semiconductor laser with frequency capture in a coherent reflectometer system. The ability of the system to reconstruct the frequency spectrum of disturbances was studied and a quantitative estimate of the signal-to-noise ratio was obtained for distributed measurements of the vibration frequency over a length of 4000 m in the frequency range 350–5600 Hz.

For comparison, the same measurements on the same reflectometer and under the same conditions of excitation of perturbations were performed using a commercial fiber laser with an ultra-narrow genera-

---

[1] The results of this research were presented and discussed at the third International Conference “Optical Reflectometry, Metrology, and Sensorics 2020” (http://or-2020.permsc.ru/, September 22–24, Perm, Russia).

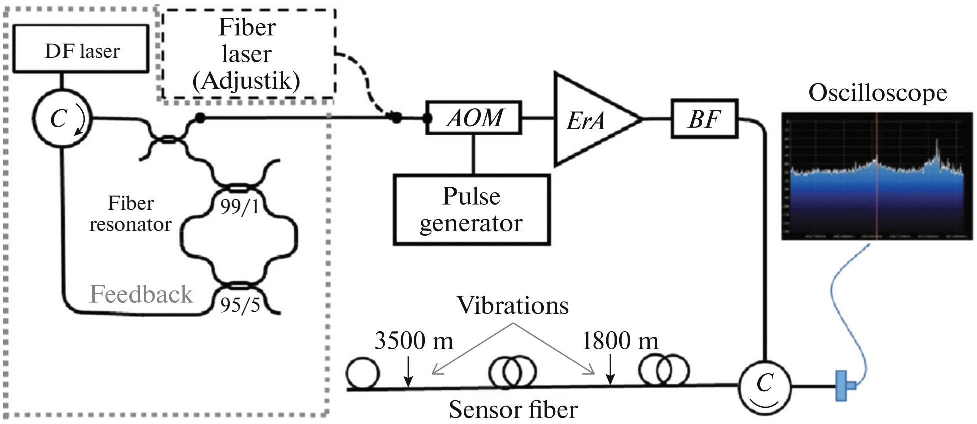

Fig. 1. The experimental setup for distributed variation of the vibration spectrum using a semiconductor or commercial fiber laser. *DF* laser, distributed-feedback semiconductor laser; *AOM*, acousto-optic modulator; *ErA*, erbium fiber amplifier; *BF*, bandpass filter; *C*, circulator.

tion line (~100 Hz). This made it possible to determine the limiting parameters of the system due to the use of a semiconductor laser with frequency capture.

The experimental configuration of a distributed vibration sensor based on a coherent reflectometer is shown in Fig. 1. The sensor fiber line (SMF28, Corning Inc.) with a length of $L_0 = 4$ km is interrogated by pulsed signals with a peak power of ~100 mW and a duration of ~100 ns (spatial resolution ~10 m). Pulses with a repetition rate f_0 formed by an acousto-optical modulator (*AOM*) from the radiation of a narrowband master oscillator are amplified by an erbium amplifier (*ErA*). A 2 GHz bandpass filter (*BF*) is used to suppress noise from spontaneous luminescence.

The sensor fiber was subjected to vibrations excited at a point at 1800 m by a piezoelectric transducer and at a point at 3500 m by a shaker. In particular, for remote measurement of the vibration spectrum the fiber at a point of 3500 m was passed through a 2-m-long plastic tube and the vibrations were transmitted to the fiber from a vibrator (shaker) adjacent to the tube. The studies were carried out at vibration frequencies of 350, 500, 1200, 3700, and 5600 Hz.

Two optical sources were used in the experiment. The first is a conventional semiconductor laser with distributed feedback that is specialized for telecommunication applications. In the free mode, the laser generates radiation at a wavelength of ~1548.5 nm with an output power of ~7.4 mW and a generation line width of ~1 MHz.

For forced operation of the laser in the frequency capture mode the fiber laser output through a feedback line containing an optical circulator and a ring fiber filter [15, 16] that is welded from two optical fiber couplers with preservation of polarization with a total length of 3.75 m is closed to itself. In the frequency capture mode, a sharp narrowing of the width of the generation line and self-stabilization of the laser frequency with the generation of one longitudinal mode in the band of less than ~6 kHz occurs [9].

The use of fiber-optic components with preservation of polarization avoids an abrupt change in the state of polarization of the laser, which is the main source of instability [17] that disrupts laser generation in the frequency capture mode. A laser diode current of 50 mA (a threshold current of 10 mA) and an operating temperature of 25°C were experimentally selected as the laser configurations to achieve the best result and were stabilized with an accuracy of ~0.3% to maintain the laser operation in the self-locking frequency of the external resonator [18].

The entire laser system was placed in a polyurethane thermal and noise insulating box to protect the laser from external disturbances. Under these conditions, the laser frequency drift was mainly determined by the temperature stability of the external ring resonator and was estimated to be less than ~30 MHz/min. The duration of continuous operation of the laser in the frequency self-locking mode (between mode hop events) was up to ~30 min.

The second laser used in the experiment as a reference master oscillator was a commercial fiber laser (Koheras Adjustik, NKT Photonics) operating at a wavelength of ~1552.5 nm with an output power of ~40 mW and a line width of ~100 Hz. According to the specification, the laser has a frequency drift of ~1 MHz/min.

In the process of polling the sensor fiber, each probe pulse introduced into the fiber generates a backscatter signal, which is digitized by a fast photodetector using a digital converter. The original trace consists of $M = 8000$ points corresponding to a uniform distribution along the length of the fiber, i.e., the sampling resolution is ~0.5 m. It used $N = 932$ sequentially recorded traces that form the $N \times M$ $\{s_{nm}\}$ signal matrix for the vibration analysis.

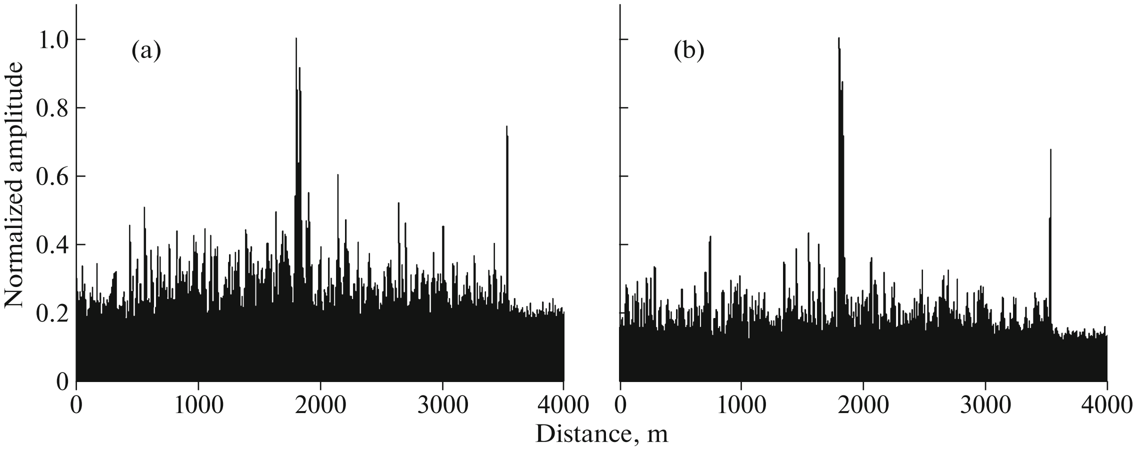

Fig. 2. Examples of traces obtained using a semiconductor (a) and a commercial fiber laser (b). The peaks in reflection patterns show the locations of the application points of the vibration.

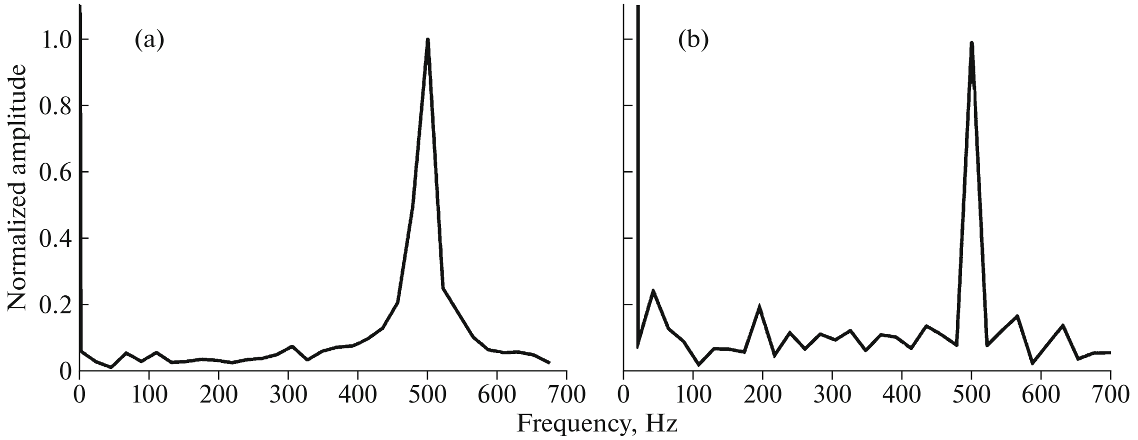

Fig. 3. The spectrum of vibration frequencies at a frequency of 500 Hz from vibrations recorded at a point of ~3500 m when using a semiconductor laser with frequency capture of an external resonator (a) and commercial fiber laser (b).

During processing, each matrix element s_{nm} was averaged over the 20 closest 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 $w = 21$. This procedure smooths the recorded traces, i.e., it filters out the noise of the signal outside the spatial spectrum, which corresponds to a resolution of ~10 m. Further signal processing was applied to the columns of the matrix (i.e., to the time domain): application of the moving differential algorithm [13, 14] reduces the noise background and leads to the resulting signal, as given in Fig. 2, with pronounced peaks at the positions of the applied perturbations.

The spectral function $U(f_k, x_m) = FFT(\tilde{s}_{nm}, m, k)$ of the frequencies $f_k = f_0(k-1)/(N-1)$ describes the vibration spectrum at a fiber point $x_m = L_0(m-1)/(M-1)$, which is obtained from $\{\tilde{s}_{nm}\}$ fast Fourier transform index n.

Figure 3 shows the $U(f_k, x_m)$ spectrum recorded for an oscillation frequency of ~500 Hz at the point $x_m \sim 3500m$ obtained using a semiconductor (Fig. 3a) and commercial laser (Fig. 3b). Several (5–10) measurements were performed for each frequency to reduce fluctuations in the response [19] (associated with stochastic fluctuations of the peak width and background level); the presented signal-to-noise ratios are the averaged values for each frequency.

For a configuration with a semiconductor laser (Fig. 3a), the peak of the spectrum exceeds the maximum noise level by approximately ten times, providing reliable recognition of the applied oscillation frequency. The signal-to-noise ratio, defined as the ratio between the peak value of the spectrum and the root mean square level of the spectral noise, is estimated as ~9.4 dB. For the configuration with a commercial laser (Fig. 3b), these values are almost the same, ~9 times and 9.0 dB, respectively.

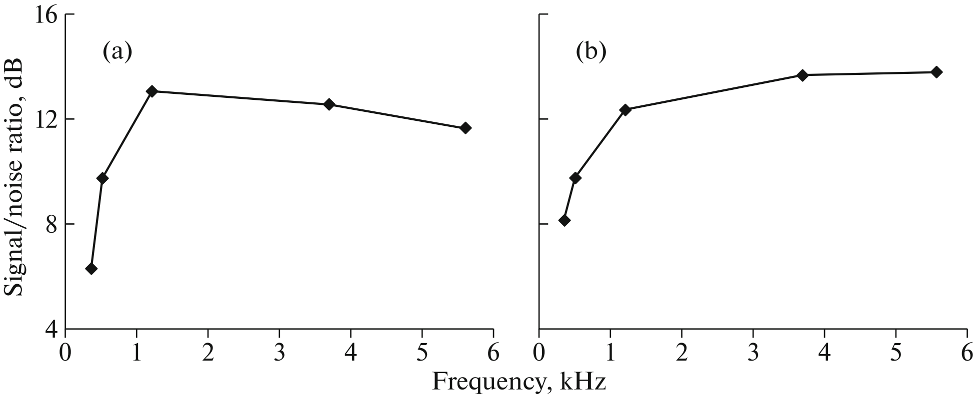

Fig. 4. The signal-to-noise ratio as a function of frequency from vibrations recorded at a point of ~3500 m when using a semiconductor laser with frequency capture of an external resonator (a) and commercial fiber laser (b).

The dependence of the signal-to-noise ratio on the oscillation frequency is shown in Fig. 4. It can be seen that the signal-to-noise ratio gradually increases with increasing vibration frequency. This can be explained by the narrowing of the peak of the spectrum reconstructed using the fast Fourier transform with an increase in the number of oscillation periods over a fixed measurement time. At low vibration frequencies, both configurations have the same signal to noise ratio. For higher frequencies, slightly lower signal-to-noise ratios are obtained with a semiconductor laser (Fig. 4a) due to a faster drift of its frequency; at an oscillation frequency of 5600 Hz the difference in values for the two configurations is ~10%. Over the entire range of vibration frequencies of 500 Hz and higher the signal-to-noise ratio in both cases exceeds ~8 dB.

Thus, we quantitatively substantiated the use of a conventional telecommunication semiconductor laser in the frequency capture mode of an external resonator to operate as a master oscillator of a coherent reflectometer that is specialized for detection of distributed vibrations. The obtained signal-to-noise ratios confirm the ability of the system to perform distributed measurement of vibration frequencies in the 500–5600 Hz range with a spatial resolution of ~10 m.

FUNDING

This study was supported by the Russian Science Foundation (project 18-12-00457) and the Russian Foundation for Basic Research (project nos. 18-42-732001 r_mk, 19-42-730009 r_a).

REFERENCES

1. Gorbulenkov, V., Leonov, A., Marchenko, K., and Treshchikov, V., *Foton-Ekspress,* 2014, no. 5 (117), p. 12.
2. Nesterov, E., Ozerov, A., Nanii, O., and Treshchikov, V., *Foton-Ekspress,* 2011, no. 6 (94), p. 122.
3. Lu, Y., Zhu, T., Chen, L., and Bao, X., *J. Lightwave Technol.,* 2010, vol. 28, no. 22, p. 3243.
4. Fomiryakov, E.A., Kharasov, D.R., Nikitin, S.P., Nanii, O.E., and Treshchikov, V.N., *Foton-Ekspress,* 2019, no. 6 (158), p. 48. https://doi.org/10.24411/2308-6920-2019-16019
5. Peng, F., Wu, H., Jia, X.-H., Rao, Y.-J., Wang, Z.-N., and Peng, Z.-P., *Opt. Express,* 2014, vol. 22, no. 11, p. 13804. https://doi.org/10.1364/OE.22.013804
6. Spirin, V.V., Castro, M., López-Mercado, C.A., Mégret, P., and Fotiadi, A.A., *Laser Phys.,* 2012, vol. 22, p. 760. https://doi.org/10.1134/S1054660X12040214
7. Spirin, V.V., López -Mercado, C.A., Mégret, P., and Fotiadi, A.A., *Laser Phys. Lett.,* 2012, vol. 9, p. 377. https://doi.org/10.7452/lapl.201110138
8. Spirin, V.V., López -Mercado, C.A., Kinet, D., Mégret, P., Zolotovskiy, I.O., and Fotiadi, A.A., *Laser Phys. Lett.,* 2013, vol. 10, p. 015102. https://doi.org/10.1088/1612-2011/10/1/015102
9. López -Mercado, C.A., Spirin, V.V., Escobedo, J.L.B., Lucero, A.M., Mégret, P., Zolotovskii, I.O., and Fotiadi, A.A., *Opt. Commun.,* 2016, vol. 359, p. 195. https://doi.org/10.1016/j.optcom.2015.09.076
10. Spirin, V.V., Escobedo, J.L.B., Korobko, D.A., Mégret, P., and Fotiadi, A.A., *Opt. Express,* 2020, vol. 28, p. 478. https://doi.org/10.1364/OE.28.000478
11. Escobedo, J.L.B., Spirin, V.V., López -Mercado, C.A., Lucero, A.M., Mégret, P., Zolotovskii, I.O., and Fotiadi, A.A., *Results Phys.,* 2017, vol. 7, p. 641. https://doi.org/10.1016/j.rinp.2017.01.013
12. Spirin, V.V., López -Mercado, C.A., Mégret, P., and Fotiadi, A.A., in *Selected Topics on Optical Fiber Technologies and Applications, InTech*, 2018. https://doi.org/10.5772/intechopen.72553
13. López-Mercado, C.A., Jason, J., Spirin, V.V., Escobedo, J.L.B., Wuilpart, M., Mégret, P., Korobko, D.A., Zolotovskiy, I.O., and Fotiadi, A.A., *Proc. SPIE,* 2018, vol. 10680, p. 106802S. https://doi.org/10.1117/12.2307683
14. Escobedo, J.L.B., Jason, J., López-Mercado, C.A., Spirin, V.V., Wuilpart, M., Mégret, P., Korobko, D.A., Zolotovskiy, I.O., and Fotiadi, A.A., *Results Phys.,*

2019, vol. 12, p. 1840.
https://doi.org/10.1016/j.rinp.2019.02.023

15. Spirin, V.V., López-Mercado, C.A., Kablukov, S.I., Zlobina, E.A., Zolotovskiy, I.O., Mégret, P., and Fotiadi, A.A., *Opt. Lett.,* 2013, vol. 38, p. 2528.
https://doi.org/10.1364/OL.38.002528

16. López -Mercado, C.A., Spirin, V.V., Kablukov, S.I., Zlobina, E.A., Zolotovskiy, I.O., Mégret, P., and Fotiadi, A.A., *Opt. Fiber Technol.,* 2014, vol. 20, p. 194.
https://doi.org/10.1016/j.yofte.2014.01.011

17. Escobedo, J.L.B., Spirin, V.V., López -Mercado, C.A., Mégret, P., Zolotovskii, I.O., and Fotiadi, A.A., *Results Phys.,* 2016, vol. 6, p. 59.
https://doi.org/10.1016/j.rinp.2016.01.017

18. Korobko, D.A., Zolotovskii, I.O., Panajotov, K., Spirin, V.V., and Fotiadi, A.A., *Opt. Commun.,* 2017, vol. 405, p. 253.
https://doi.org/10.1016/j.optcom.2017.08.040

19. Hartog, A.H., *An Introduction to Distributed Optical Fibre Sensors,* Boca Raton, FL: CRC Press, 2017.
https://doi.org/10.1201/9781315119014