ISSN 8756-6990, Optoelectronics, Instrumentation and Data Processing, 2023, Vol. 59, No. 1, pp. 66–76.

OPTICAL-PHYSICAL METHODS OF RESEARCH AND MEASUREMENT

Brillouin Lasers and Sensors: Trends and Possibilities

A. A. Fotiadi[1,2*], D. A. Korobko[1], and I. O. Zolotovskii[1]

[1] *Ulyanovsk State University, Ulyanovsk, 432017 Russia*

[2] *University of Mons, Mons, B-7000 Belgium*

Received October 31, 2022; revised November 22, 2022; accepted December 2, 2022

Abstract—Novel techniques of photonics based on stimulated Brillouin scattering (SBS) in optical fibers are considered. The main attention is paid to the original schemes of narrow-band low-noise lasers and their possible applications in distributed fiber sensors.

DOI: 10.3103/S8756699023010065

Keywords: *fiber lasers, stimulated Brillouin scattering, distributed fiber sensors*

INTRODUCTION

Stimulated Brillouin scattering (SBS) [1, 2] in standard fibers is characterized by a uniform gain line with a width of ~30 MHz and a large dynamic range in terms of the absolute gain of the resonant signal power [3–7]. The upper gain limit of $\sim 10^{12}$ corresponds to the generation of SBS from thermal noise at a typical threshold pump power of ~10 mW per kilometer of telecommunication fiber. Such low threshold powers and giant gain make it possible to create SBS devices based on standard semiconductor laser diodes and fiber cavities. However, in order for a semiconductor laser to generate SBS in a fiber resonator, its own generation line must be preliminarily narrowed by several orders of magnitude. Simple and effective techniques for narrowing the generation line of a semiconductor laser make it possible to create inexpensive narrow-band Brillouin sources that are compact and reliable and have a low phase noise.

Over the past few years, we have proposed a number of solutions for Brillouin lasers with a Lorentzian linewidth up to 500 Hz, which are fully welded fiber configurations that combine a laser diode and several standard telecommunication components. The possibility of simultaneous generation at two strictly related frequencies makes these solutions attractive for use as a master oscillator in distributed sensors based on both Rayleigh scattering and Brillouin scattering in optical fibers.

The purpose of this work is to describe the original ideas and individual technical solutions underlying the developed configurations of narrow-band lasers [8–10] as well as the features of their possible applications in distributed fiber sensors of acoustic vibrations, temperature, and pressure [11–15].

1. NARROWING OF LASER GENERATION LINE AND ITS STABILIZATION

The narrowing of the linewidth and the stabilization of the generation of a semiconductor laser are of considerable research interest due to the great demand for compact, inexpensive, and narrow-band laser sources with high coherence, which are necessary for a large number of applications [16–20]. They are high-resolution spectroscopy, coherent optical communication, distributed optical monitoring, optical spectrum analysis, and microwave photonics [21–24]. The generation linewidth of standard semiconductor DFB lasers (distributed feedback lasers) is usually several megahertz [25]. Self-locking of the laser frequency by external feedback is one of the most promising techniques for narrowing the laser line. To ensure the effect, part of the optical radiation emitted by a laser is returned to its resonator, thereby the threshold at the locked frequency gets lower [26]. This relatively simple technique makes it

*E-mail: Andrei.Fotiadi@gmail.com

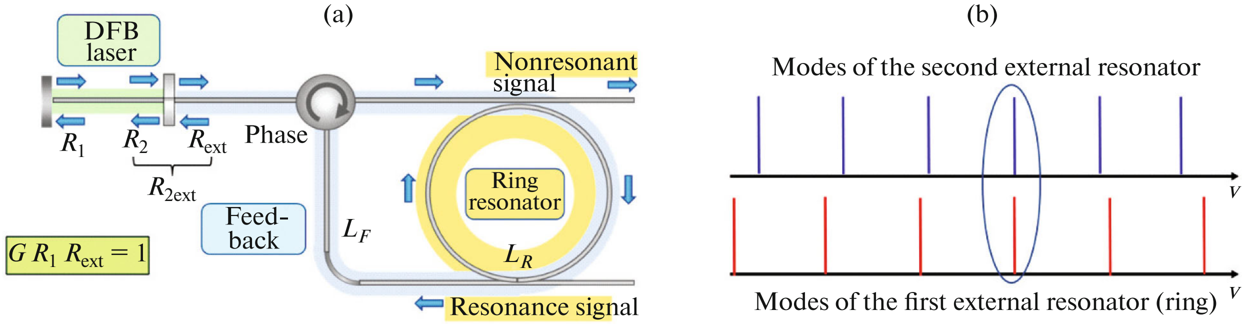

Fig. 1. Pattern of frequency lock-on of an external ring resonator by a DFB laser. (a) Schematic diagram of a laser with an external resonator and (b) mode position required to maintain stable operation of the laser in frequency lock mode.

possible to develop inexpensive narrow-band laser sources based on standard laser diodes, which makes it more attractive than conventional laser systems based on active feedback. One of the most interesting laser configurations with frequency lock-on is based on a narrow-band optical filter in a weak feedback loop [27]. In particular, current studies are associated with the use of microresonators [28–35]. By using such resonators in the whispering gallery mode, the linewidth of a semiconductor laser can be reduced to the subkilohertz frequency range in a reliable and compact configuration [36]. The disadvantages of systems based on microresonators with a huge quality factor ($\sim 10^{11}$) are the complexity of tuning, adjustment, and also the connection of fiber elements and nonfiber elements.

An alternative option is fiber resonator systems, which have a lower quality factor, but are capable of providing a similar line narrowing. In particular, such solutions are of great interest for generating the radio frequency spectrum and distributed Brillouin monitoring, in which the fiber resonator can simultaneously serve as a nonlinear medium for generating of Brillouin radiation with a frequency shift [37–43].

The approach developed in this work is based on the fact that a distributed feedback semiconductor laser (DFB laser) captures the natural frequency of an external fiber resonator, as shown in Fig. 1*a*. External fiber resonators can be made from standard components and have a low cost. To implement frequency self-locking, the radiation of a semiconductor DFB laser is passed through an external high-Q ring resonator, and then it returns to the DFB laser resonator through a feedback fiber, imposing on it generation at the natural frequency of the external resonator. A significant (more than 1000 times) narrowing of the generation line of a standard inexpensive DFB laser connected to an external fiber ring resonator has been demonstrated [44, 45]. After frequency lock, any slow change in the frequency of the fiber resonator mode (for example, due to temperature fluctuations) leads to a simultaneous change in the laser frequency. However, in real conditions with environmental noise, the laser operates stably with generation of one longitudinal resonator mode for several seconds. These intervals of stable operation are interrupted by short-term jumps in the generation intensity caused by the resonator mode jump. Despite the fact that precise stabilization of the pump current and fixation of the fiber temperature make it possible to increase these intervals up to tens of minutes, even rare mode jumps that disrupt stable generation in the frequency lock mode make many practically important applications of lasers of this type impossible [46].

The reason for the instabilities is illustrated in Fig. 1b. This is a violation of the balance of the lengths of the ring interferometer and the optical feedback fiber in the laser configuration caused by changes in the ambient temperature. The laser configuration is a combination of a semiconductor laser and two external resonators (a ring interferometer and a feedback fiber resonator) [47]. When a semiconductor laser operates in the ring frequency locking mode, its generation frequency coincides with the resonant frequency of the ring. However, stable operation of the laser in the mode is possible only when the resonant frequency of the ring is also resonant for the second external resonator. Therefore, stable operation of the laser in the frequency lock mode requires continuous tuning of the resonance of the second external resonator to the resonance of the ring. This can be done by modulating the laser diode current or by controlling the fiber length of the second external resonator using a piezoactuator (see Fig. 1a). For these purposes, a circuit with active optoelectronic feedback controlled by a simple USB-DAQ controller was used.

2. SINGLE-FREQUENCY LASER

The authors of [8] proposed a fiber configuration in which the generation lines are narrowed and the operation of the semiconductor DFB laser is stabilized due to frequency lock-on in combination with active optoelectronic feedback controlled by a simple USB-DAQ (USB data acquisition) controller. It is important that the generation line is narrowed by the frequency locking, while active feedback only helps to maintain this passive stabilization mode. Since it is difficult to implement these electronic circuits, such a combined solution is much less expensive than all known active stabilization circuits, in particular, based on the method of Pound–Drever–Hall (PDH) and Hansch–Couillaud which is commonly used in fiber lasers [48–50]. In addition, the technique makes it possible to control and adjustment of the laser linewidth.

The experimental configuration of a semiconductor DFB laser coupled to a ring fiber resonator is shown in Fig. 2a. A standard laser diode (MITSUBISHI FU-68PDF-V520M27B) operating at a wavelength of 1534.85 nm with an output power of ∼5 mW is equipped with a built-in optical isolator that attenuates the back-radiation power by ∼30 dB. The isolator eliminates the effects of uncontrolled back reflection and reduces the feedback power received through the external ring resonator. To implement the frequency lock-on, laser radiation passes through an optical circulator and is introduced through a coupler into a ring resonator, which is formed by couplers 95/5 and 99/1 and includes ∼4 m of standard SMF-28 fiber. The second coupler sends some of the radiation circulating in the resonator through the circulator back to the DFB laser, providing passive feedback to frequency lock-on.

When the passive feedback loop is open, the laser operates in free mode. Its total generation linewidth is approximately 10 MHz. When the feedback loop is closed, there is a frequency lock mode with a sharp (∼3000 times) narrowing of the laser generation line measured by the self-heterodyne method to several kHz [51]. In the self-locking mode with passive feedback, the width of the laser generation line keep its minimum value for 1–100 s (depending on the level of environmental noise). The rest of the time, it slowly fluctuates in the range of 2.8–14 kHz until a mode jumps. The problem of optoelectronic feedback based on an inexpensive multifunctional USB controller DAQ NI USB-6009 (National Instrument, United States) controlled by a PC is to maintain the operation of the laser in the self-locking mode (i.e., to prevent the detuning frequency from operating range of a stable generation), avoiding mode jumps. For this purpose, the radiation power reflected by the ring resonator (port B) and recorded by the photodetector must be kept constant at a given level. The deviation of the reflected power parameter from the set value is used as an error signal for the DAQ microcontroller, which can adjust the operating frequency of the laser in the range of about 1 GHz due to the slight deviation of the laser diode current. When the power parameter R is strictly related with some set value R_{set}, both the laser frequency detuning from the ring resonator transmission peak and the laser linewidth are stabilized using optoelectronic feedback. The curves in Fig. 2b show the self-heterodyne laser spectra recorded with various set values R_{set}. At a minimum $R_{\text{set}} = R_{\text{min}} \sim 0.08$, the laser frequency coincides with one of the transmission peaks of the ring resonator, and the generation linewidth takes on a minimum value of ∼2.8 kHz. Detailed characteristics of the laser are described in [8].

3. TWO-FREQUENCY BRILLOUIN LASER

The authors of [9] developed a fiber configuration for a two-frequency Brillouin laser. In the new configuration shown in Fig. 3a, the same ring fiber resonator is used both for frequency lock-on of the DFB laser and for generating the Stokes component of the Brillouin radiation. Just like in the previous case, a simple and inexpensive USB-DAQ card is used to stabilize the system, preventing mode jumps. It is important that the stable operation of the laser at two strictly coupled frequencies is provided by the frequency lock-on, while the active feedback loop only helps to maintain this mode. The frequency lock-on keeps the DFB laser in continuous synchronization with the external ring resonator, providing ideal laser-to-ring coupling for resonant (low-noise) Brillouin pumping.

The measured characteristics of a simple two-frequency laser are similar to characteristics of expensive analogues. The Lorentz line width (measured by the method from [52, 53]) at the pump and Stokes signal frequencies is <270 Hz and <110 Hz, respectively, and the width of the radio frequency (RF) beat spectrum between them is <300 Hz (Fig. 4a). This is an important result, especially considering that the system does not require serious temperature stabilization. The laser output power

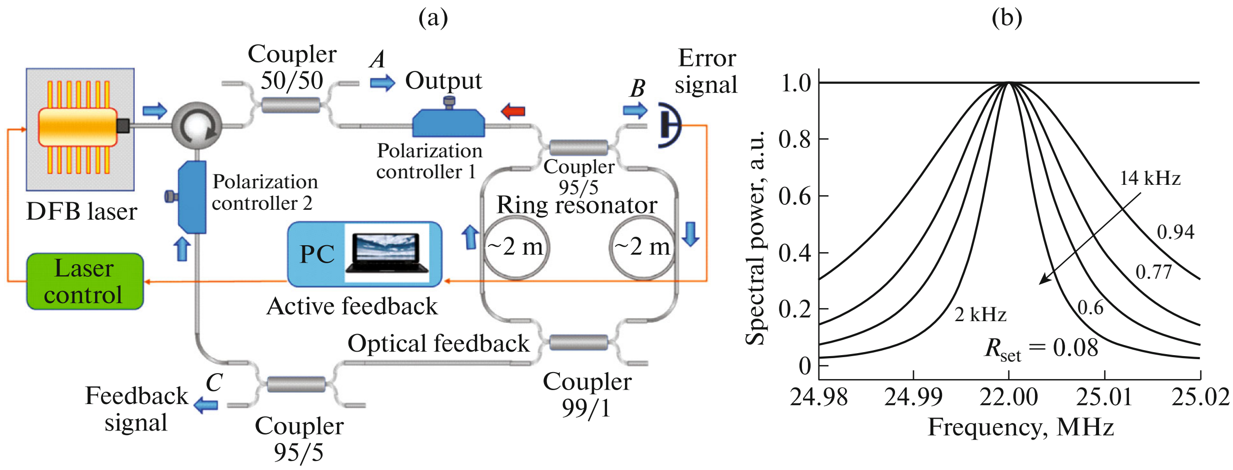

Fig. 2. Pattern of a single-frequency laser. (a) Schematic diagram of a laser and (b) self-heterodyne spectra of a laser stabilized at different levels of the signal B (fraction of the maximum).

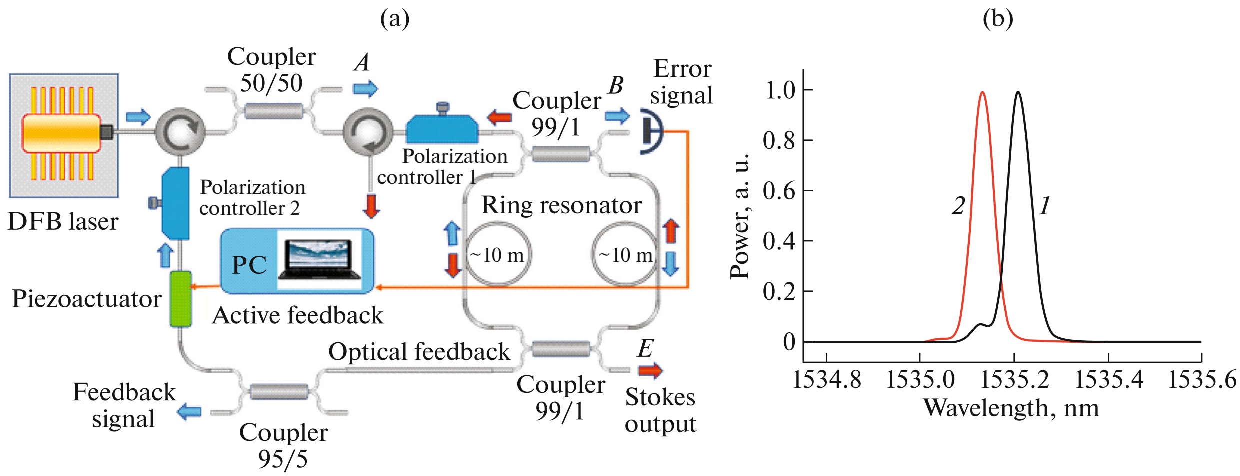

Fig. 3. Pattern of a two-frequency laser. (a) Experimental configuration of a two-frequency Brillouin laser and (b) optical spectra for two laser channels: Stokes frequency (*1*) and pump frequency (*2*).

is $\sim$9 mW and $\sim$100 μW for pump and Stokes radiation, respectively, and allows further power scaling by external amplifiers. In this case, the laser power at the pump frequency can be amplified using an erbium doped fiber amplifier (EDFA), while using an external Brillouin amplifier (made from the same fiber as the ring resonator and pumped by a laser amplified in EDFA) is preferable (and naturally) for narrowband amplification of the Stokes signal. The operating frequencies of the laser are strictly tied to the resonances of the ring resonator, and their drift measured in the experiment ($\sim$8.8 MHz min^{-1}) is mainly determined by changes in the ambient temperature.

Ambient temperature drift is the main source of instability in a two-frequency laser. To reduce this influence, the laser configuration is placed in a foam box, but this does not prevent the slow drift of the laser frequency. The use of an optional thermal controller applied to the entire laser configuration limits laser frequency drift and minimizes RF spectrum broadening. Changes in ambient temperature affect both the length of the ring resonator and the length of the feedback loop fiber, changing the relative position of their resonant frequencies. These resonances must coincide to stabilize laser operation. The electronic feedback circuit works against thermal noise by always trying to keep the resonances aligned. To do this, it adjusts the phase delay in the optical feedback loop by smoothly changing the voltage applied to the piezoactuator. However, the dynamic range of the piezo actuator is limited. When its limit is exhausted, the phase must be reset for an integer number of periods, and this is possible only through a step change in the voltage on the piezoactuator. Control signal jumps destabilize the laser for a short

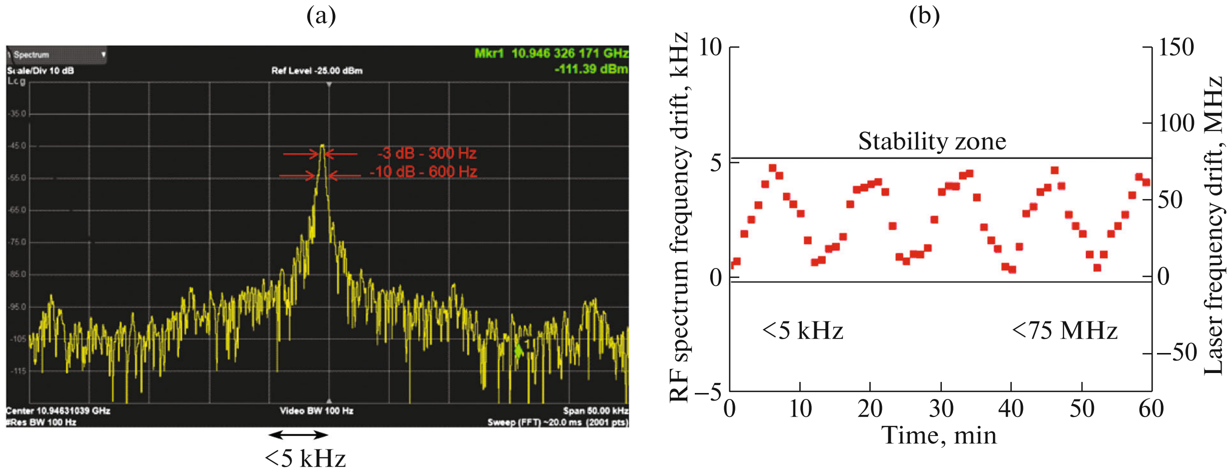

Fig. 4. Characteristics of a two-frequency laser. (a) RF spectrum of the beat signal between two output radiations of a two-frequency laser and (b) long-term evolution of the peak frequency of the beat spectrum during active thermal stabilization of the laser configuration as a whole.

time. Thus, the stabilization system (on a piezoactuator) makes it possible to stabilize laser generation as long as the laser generation frequency is within a certain frequency range. When it leaves this range under the influence of temperature drift, a mode jumps. With a characteristic laser frequency drift of ~8 MHz min^{-1} (under laboratory conditions), the typical time between mode jumps is ~7–10 min.

Additional thermal control of the entire laser module was used to permanently stabilize the laser. The result is shown in Fig. 4b. An electrical signal applied to a piezoactuator was used as an error signal in this system. When its deviation from the mean value exceeded a certain value, the temperature of the system changed in the direction that reduced this deviation. A typical change in temperature inside the laser module for one thermal pulse was ~0.1°C, and the characteristic time of temperature fluctuations was 5–7 min. To control the frequency drift, a technique was developed based on continuous measurement of the peak of the radio frequency spectrum of optical radiation beats recorded from two laser outputs. This ensured long-term stability of the laser. In this case, the laser frequency drift was <80 MHz, and the variations in the peak frequency of the RF beat spectrum were limited to <5 kHz. It is important that keeping the beat frequency within this range completely prevented mode jumps.

4. BRILLOUIN LASER BASED ON A HIGH-Q RESONATOR

The authors of [10] proposed and studied another configuration of a narrow-band two-frequency laser (Fig. 5a). Unlike previous two-frequency laser configurations, a fiber ring resonator made (and then included in the configuration) from one fiber coupler instead of two fiber couplers as usual was used. The new laser design made it possible to reduce optical losses in the ring resonator (by a factor of two compared to a ring resonator with two input fibers) providing an increased quality factor. Consequently, the consumer properties of the two-frequency laser were significantly improved. The output power for Stokes radiation is increased by two times. The threshold power of the Brillouin generation is reduced by a factor of two compared with previous works. The Lorentzian linewidth of the laser radiation has become 30% narrower than that previously demonstrated in [9].

Generally, the laser produces continuous narrow-band radiation simultaneously at the pump and Stokes signal frequencies. The laser diode operates in the ring fiber resonator frequency locking mode, which narrows the Lorentz linewidth by a factor of ~10 000 to ~400 Hz. The operation of the laser in this mode is supported by an active optoelectronic feedback controlled by a simple microcontroller. The accumulation of narrow-band pump laser radiation inside the ring resonator makes the ring resonator work as a continuous-wave Brillouin laser radiating with a Lorentzian spectral linewidth of ~75 Hz (Fig. 5b). As is known, this is the narrowest laser linewidth ever recorded with DFB lasers in a frequency lock-on configuration through an external fiber resonator. Previously, the Lorentz linewidth ~125 Hz was obtained with a more complex configuration by locking the frequency of a fiber grating [38] (for

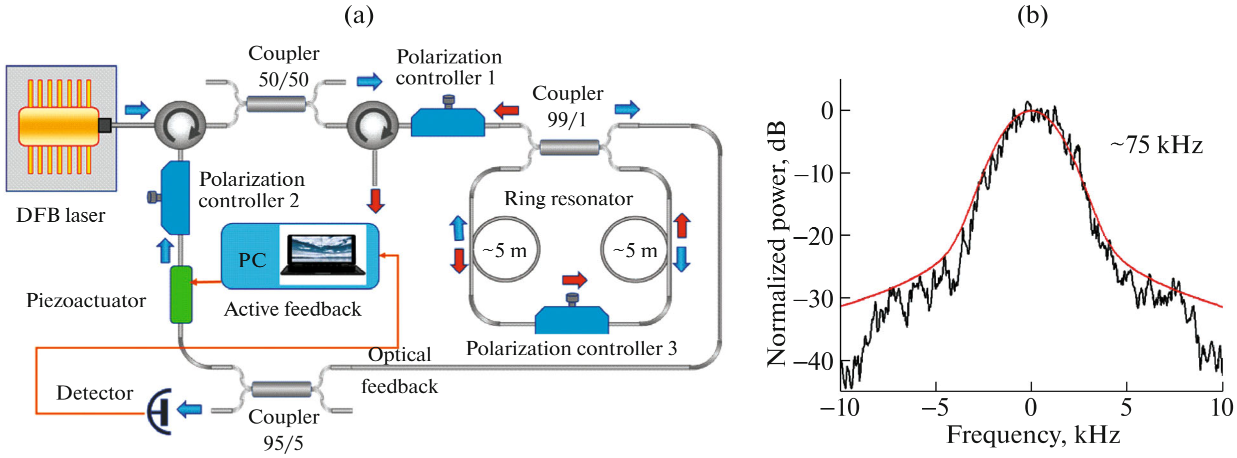

Fig. 5. Pattern of a Brillouin laser based on a high-Q resonator. (a) Experimental configuration of a Brillouin laser and (b) self-heterodyne optical spectrum of a laser.

comparison, the linewidth of a commercial laser with frequency lock in the whispering gallery mode is ~300 Hz [54]); the typical Lorentz linewidth of a Brillouin laser (on a fiber resonator 25 km) is ~30 Hz [55]. The threshold pump power in our experiment is ~1.5 mW. The Stokes intensity relative noise is < -90 dB Hz^{-1}, and the phase noise is < -100 dB Hz^{-1} for radio frequencies >30 kHz.

Comparison of Figs. 2a, 3a, and 5a makes it possible to see the fundamental difference in the laser stabilization in the operating mode. In the configurations of the first two lasers based on the frequency locking, the feedback signal is increased when the semiconductor laser locks on to the frequency of the resonator. In the latter case, it seems to take on a minimum value when locking the frequency. The fact that this is not the case becomes clear if we take into account the induced birefringence in the ring resonator of the laser, which changes the polarization of light during a single passage of the ring to perpendicular. The discovered effect was amplified and used in a new configuration of a polarization-maintaining fiber laser [56]. Its advantage is a much better resistance to external influences than all previous configurations of narrow-band lasers considered in this work.

5. APPLICATIONS OF LASERS FOR DISTRIBUTED MEASUREMENTS

Although distributed Rayleigh and Brillouin scattering fiber sensors [57–62] are currently widely used in the oil and gas industry, nuclear power, and construction of large infrastructure facilities, their relatively high cost remains the main factor limiting their applications only by resource-intensive industries. The key and most expensive part of the analyzer of such a sensor is the master oscillator module. The configuration of a single-frequency polarization-maintaining fiber laser developed in [12] was tested as a master source in a reflectometric fiber system of a distributed vibration sensor. The ability of a coherent reflectometer based on a semiconductor laser with frequency lock to detect and localize acoustic disturbances in a 9 km test fiber line was evaluated in an experiment. It was shown that the efficiency (signal-to-noise ratio) of vibration source detection and the accuracy of its localization is no worse than when using an expensive standard master oscillator.

The authors of [13] studied the ability of the system to restore the frequency spectrum of disturbances, and calculated a signal-to-noise ratio for distributed vibration frequency measurements over a length of 4000 m in the frequency range of 350–5600 Hz. For comparison, the same measurements using the same reflectometer under the same excitation conditions were carried out using a commercial fiber laser (Koheras Adjustik, NKT Photonics) with an ultranarrow generation 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 lock. Thus, we have quantitatively substantiated the use of a conventional telecommunication semiconductor laser in the lock-on mode of the external resonator frequency to operate as a master oscillator of a coherent reflectometer specialized for distributed vibration detection. The values of the signal-to-noise ratio confirm the ability of the system to perform a distributed measurement of vibration frequencies with a spatial resolution of ~10 m.

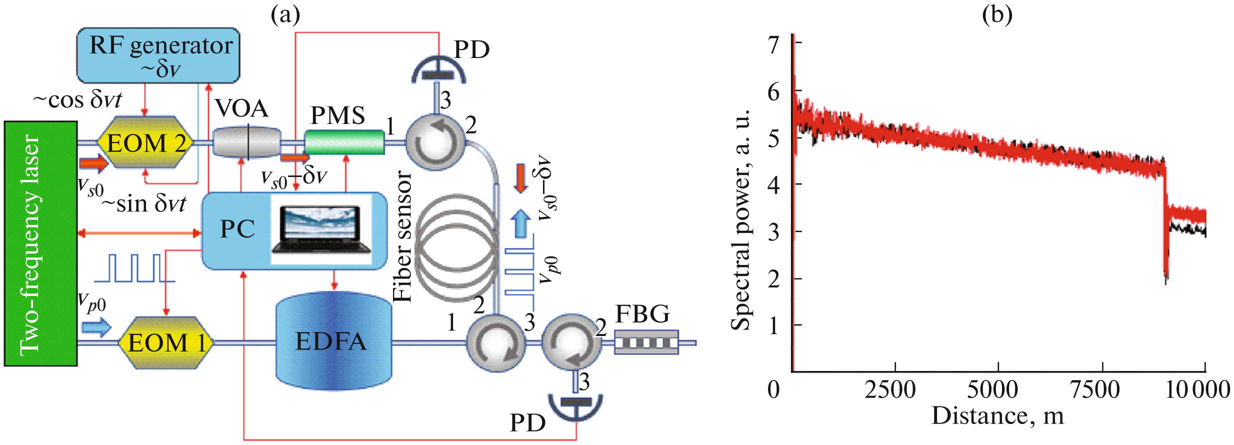

Fig. 6. Application of a two-frequency laser for distributed measurement of temperature and voltage. (a) Schematic diagram of an analyzer and (b) typical BOTDA reflectograms recorded for ~9 km fiber line on developed (gray curve) and commercial (black curve) analyzers. Designations are electro-optic modulator (EOM), variable optical attenuator (VOA), polarizing mixer (PMS), fiber Bragg grating (FBG), and photodetector (PD).

The ability to continuously generate two strictly coupled frequencies makes the laser efficient for many applications, including high-resolution spectroscopy, phase-coherent optical communication, distributed fiber monitoring, coherent optical spectrum analysis, and microwave photonics. For many of them, a subkilohertz generation linewidth is a necessary condition; for others, the simplicity of the configuration is more important. The authors of [15] studied the possibility of using a two-frequency narrow-band laser shown in Fig. 3a as a master oscillator of a Brillouin analyzer. In contrast to other similar solutions based on Brillouin lasers [63, 64], a frequency locking laser was used for the first time in the work. This idea was borrowed later in [65].

The measured laser characteristics significantly exceed the requirements for laser modules (< 15 kHz) commonly used in BOTDA (Brillouin optical time-domain analyzer) [66]. Figure 6a shows the optical layout of the BOTDA designed to work with a distributed fiber temperature and tension sensor. The use of a laser operating at two fixed frequencies greatly simplified the BOTDA system, as it eliminated the broadband electro-optic modulator (EOM) and high-power microwave oscillator powering the EOM from the traditional BOTDA configuration based on a single narrow-band laser source. These relatively expensive devices make up a significant portion of the cost of the BOTDA system. In addition, the expensive wavelength lock electronics that were part of the Brillouin lasers proposed earlier for applications in BOTDA [63] are not used in the laser, which provides self-stabilized optical signal generation at the Stokes frequency. Instead, an inexpensive electro-optic modulator controlled by a standard RF generator with a signal up to ~1 GHz is used in the proposed BOTDA system. In this configuration, the main frequency shift (~11 GHz) is provided by the laser, and the electro-optic modulator is used only for additional frequency tuning in a small range. Moreover, the tuning range of the radio frequency generator up to 100 MHz turned out to be quite enough for all measurements that were carried out when testing the analyzer on a specially designed calibration fiber line. The ability of an inexpensive laser device to work with a BOTDA sensor has been tested under commercial BOTDA; distributed measurements of the Brillouin frequency shift in a 10 km fiber test line with a spatial resolution of 1.5 m and an accuracy of up to ~2°C are also demonstrated. Figure 6b shows typical reflectograms recorded by the BOTDA (gray curve) and commercial analyzer (black curve) (OZ-Optics, Canada). The performance of the system associated with the use of a two-frequency laser did not degrade during the measurements. The details of its work and consumer properties are described in detail in [15].

CONCLUSIONS

In this work, a standard semiconductor DFB laser was used to develop a stable narrow-band laser source. The laser is stabilized in frequency lock-on mode by means of active optoelectronic feedback controlled by an inexpensive USB-DAQ card (via modulation of the DFB laser current or a piezo actuator that controls the length of the fiber in the optical feedback circuit). For two-frequency generation, the same ring fiber resonator is used both for frequency self-locking of the DFB laser and for generating the Stokes component of Brillouin radiation. In this case, the maximum achievable values of the generation linewidth at the Brillouin frequency are determined by the quality factor of the external ring resonator. To achieve a record-breaking narrow generation line (∼75 Hz), a high-Q ring resonator made from a single fiber coupler was used. A special thermal control was applied to the entire laser unit to reduce the laser frequency drift to < 80 MHz and to suppress the mode jump. The possibility of using a narrow-band two-frequency laser as a master oscillator of the BOTDA was also studied, which greatly simplifies its design. Comparison with a commercial system demonstrated that there was no degradation in BOTDA performance due to the use of the developed two-frequency laser.

FUNDING

This work was supported by the Russian Science Foundation (project no. 18-12-00457P) and Ministry of Science and Higher Education of the Russian Federation (project no. 075-15-2021-581).

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

REFERENCES

1. V. S. Starunov and I. L. Fabelinskiĭ, "Stimulated Mandel'shtam–Brillouin scattering and stimulated entropy (temperature) scattering of light," Sov. Phys. Usp. **98**, 441–491 (1970). https://doi.org/10.1070/PU1970v012n04ABEH003903
2. A. M. Rubenchik, "On the problem of laser thermonuclear synthesis," Avtometriya **5**, 80–93 (1979).
3. M. P. Petrov and E. A. Kuzin, "Stimulated Briollouin scattering in optical fibers, and wavefront reversal," Sov. Phys. Solid State **25**, 188 (1983).
4. E. M. Dianov, A. Ya. Karasik, A. V. Lutchnikov, and A. N. Pilipetskii, "Saturation effects at backward-stimulated scattering in the single-mode regime of interaction," Opt. Quantum Electron. **21**, 381–395 (1989). https://doi.org/10.1007/BF02028181
5. G. Agrawal, *Nonlinear Fiber Optics* (Academic Press, San Diego, Calif., 2001).
6. E. Kuzin, M. Petrov, and A. Fotiadi, "Fiber-optic stimulated-Brillouin-scattering amplifier," Sov. Phys. Tech. Phys.**33**, 206–209 (1988).
7. E. A. Kuzin, M. P. Petrov, and A. A. Fotiadi, "Phase conjugation by SMBS in optical fibers," in *Optical Phase Conjugation*, Ed. by D. P. Gower (Springer-Verlag, 1994), pp. 74–96.
8. V. V. Spirin, J. L. Bueno Escobedo, D. A. Korobko, P. Mégret, and A. A. Fotiadi, "Stabilizing DFB laser injection-locked to an external fiber-optic ring resonator," Opt. Express **28**, 478–484 (2020). https://doi.org/10.1364/OE.28.000478
9. V. V. Spirin, J. L. Bueno Escobedo, D. A. Korobko, P. Mégret, and A. A. Fotiadi, "Dual-frequency laser comprising a single fiber ring cavity for self-injection locking of DFB laser diode and Brillouin lasing," Opt. Express **28**, 37322–37333 (2020). https://doi.org/10.1364/OE.406040
10. V. V. Spirin, J. L. Bueno Escobedo, S. V. Miridonov, M. C. Maya Sánchez, C. A. López-Mercado, D. A. Korobko, I. O. Zolotovskii, and A. A. Fotiadi, "Sub-kilohertz Brillouin fiber laser with stabilized self-injection locked DFB pump laser," Opt. Laser Technol. **141**, 107156 (2021). https://doi.org/10.1016/j.optlastec.2021.107156
11. V. V. Spirin, C. A. López-Mercado, P. Mégret and A. A. Fotiadi, "Fiber laser for phase-sensitive optical time-domain reflectometry," in *Selected Topics on Optical Fiber Technologies and Applications* (Intech, 2018), pp. 197–211. https://doi.org/10.5772/intechopen.72553
12. J. L. Bueono Escobedo, V. V. Spirin, C. A. López-Mercado, A. Márquez Lucero, P. Mégret, I. O. Zolotovskii, and A. A. Fotiadi, "Self-injection locking of the DFB laser through an external ring fiber cavity: Application for phase sensitive OTDR acoustic sensor," Results Phys. **7**, 641–643 (2017). https://doi.org/10.1016/j.rinp.2017.01.013
13. J. L. Bueno Escobedo, J. Jason, C. A. López-Mercado, V. V. Spirin, M. Wuilpart, P. Megret, D. A. Korobko, I. O. Zolotovskiy, A. A. Fotiadi, "Distributed measurements of vibration frequency using phase-OTDR with a DFB laser self-stabilized through PM fiber ring cavity," Results Phys. **12**, 1840–1842 (2019). https://doi.org/10.1016/j.rinp.2019.02.023

14. V. V. Spirin, C. A. López-Mercado, M. Wuilpart, D. A. Korobko, I. O. Zolotovsky, and A. A. Fotiadi, "Using a semiconductor laser with frequency capture as an operating optical generator of a coherent reflectometer for distributed vibration frequency measurements," Instrum. Exp. Tech. **63**, 476–480 (2020). https://doi.org/10.1134/S002044122005005X
15. C. A. Lopez-Mercado, D. A. Korobko, I. O. Zolotovskii, and A. A. Fotiadi, "Application of dual-frequency self-injection locked DFB laser for Brillouin optical time domain analysis," Sensors **21**, 6859 (2021). https://doi.org/10.3390/s21206859
16. Zh. Yang, C. Li, Sh. Xu, and Ch. Yang, *Single-Frequency Fiber Lasers*, Optical and Fiber Communications Reports, Vol. 8 (Springer, Singapore, 2019). https://doi.org/10.1007/978-981-13-6080-0
17. A. D. Vladimirskaya, M. I. Skvortsov, A. A. Wolf, I. A. Lobach, and S. I. Kablukov, "Single-frequency thulium doped fiber laser with distributed feedback," Optoelectron., Instrum. Data Process. **56**, 405–411 (2020). https://doi.org/10.3103/S8756699020040147
18. S. A. Babin and I. D. Vatnik, "Random-distributed feedback fiber lasers based on Rayleigh scattering," Optoelectron., Instrum. Data Process. **49**, 323–344 (2013). https://doi.org/10.3103/S8756699013040018
19. S. M. Popov, O. V. Butov, A. P. Bazakutsa, M. Yu. Vyatkin, Yu. K. Chamorovskii, and A. A. Fortiadi, "Random lasing in a short Er-doped artificial Rayleigh fiber," Results Phys. **16**, 102868 (2020). https://doi.org/10.1016/j.rinp.2019.102868
20. S. M. Popov, O. V. Butov, Y. K. Chamorovski, V. A. Isaev, P. Mégret, D. A. Korobko, I. O. Zolotovskii, and A. A. Fotiadi, "Narrow linewidth short cavity Brillouin random laser based on Bragg grating array fiber and dynamical population inversion gratings," Results Phys. **9**, 806–808 (2018). https://doi.org/10.1016/j.rinp.2018.03.044
21. Yu. N. Kulchin, O. B. Vitrik, A. V. Dyshlyuk, A. M. Shalagin, S. A. Babin, and A. A. Vlasov, "An interrogation technique for fiber Bragg grating sensors based on optical time-domain reflectometry," Optoelectron., Instrum. Data Process. **44**, 178–182 (2008). https://doi.org/10.3103/S8756699008020131
22. S. A. Babin, A. G. Kuznetsov, and I. S. Shelemba, "Comparison of temperature distribution measurement methods with the use of the Bragg gratingsand Raman scattering of light in optical fibers," Optoelectron., Instrum. Data Process. **46**, 353–359 (2010). https://doi.org/10.3103/S8756699010040084
23. E. G. Shapiro and D. A. Shapiro, "Optimization of the capacity of a fiber communication line with nonlinear memory," Optoelectron., Instrum. Data Process. **54**, 411–418 (2018). https://doi.org/10.3103/S8756699018040143
24. I. Sh. Steinberg, P. E. Tverdokhleb, and A. Yu. Belikov, "Analysis and imaging of internal inhomogeneities in transparent optical materials by three-dimensional laser heterodyne microprobing," Optoelectron., Instrum. Data Process. **54**, 546–556 (2018). https://doi.org/10.3103/S8756699018060031
25. Z. Fang, H. Cai, G. Chen, and R. Qu, *Single Frequency Semiconductor Lasers*, Optical and Fiber Communication Reports, Vol. 9 (Springer, Singapore, 2017). https://doi.org/10.1007/978-981-10-5257-6
26. K. Petermann, "External optical feedback phenomena in semiconductor lasers," IEEE J. Sel. Top. Quantum Electron. **1**, 480–489 (1995). https://doi.org/10.1109/2944.401232
27. J. Ohtsubo, *Semiconductor Lasers: Stability, Instability and Chaos*, Springer Series in Optical Sciences, Vol. 111 (Springer, Berlin, 2013). https://doi.org/10.1007/978-3-642-30147-6
28. R. R. Galiev, N. G. Pavlov, N. M. Kondratiev, S. Koptyaev, V. E. Lobanov, A. S. Voloshin, A. S. Gorodnitskiy, and M. L. Gorodetsky, "Spectrum collapse, narrow linewidth, and Bogatov effect in diode lasers locked to high-Q optical microresonators," Opt. Express **26**, 30509–30522 (2018). https://doi.org/10.1364/OE.26.030509
29. W. Liang, V. S. Ilchenko, D. Eliyahu, A. A. Savchenkov, A. B. Matsko, D. Seidel, and L. Maleki, "Ultralow noise miniature external cavity semiconductor laser," Nat. Commun. **6**, 7371 (2015). https://doi.org/10.1038/ncomms8371
30. T. Lan, Zh. Cao, L. Huang, Yu. Li, F. Li, L. Jiang, P. I. Iroegbu, L. Dang, Q. Gao, L. Liang, K. Mei, S. Fu, G. Yin, and T. Zhu, "Ultra-narrow-linewidth DFB laser array based on dual-cavity feedback," Opt. Express **30**, 14617–14628 (2022). https://doi.org/10.1364/OE.447483
31. F. Li, L. Huang, L. Dang, G. Yin, L. Gao, T. Lan, Yu. Li, L. Jiang, L. Shi, and T. Zhu, "Self-adaptive single frequency laser assisted by distributed feedbacks," (2020). arXiv:2011.13840 [physics.optics]
32. J. Geng, L. Yang, Sh. Zhao, and Yo. Zhang, "Resonant micro-optical gyro based on self-injection locking," Opt. Express **28**, 32907–32915 (2020). https://doi.org/10.1364/OE.405974
33. D. Huang, M. A. Tran, J. Guo, J. Peters, T. Komljenovic, A. Malik, P. A. Morton, and J. E. Bowers, "High-power sub-kHz linewidth lasers fully integrated on silicon," Optica **6**, 745–752 (2019). https://doi.org/10.1364/OPTICA.6.000745

34. Sh. Shao, J. Li, Yu. Wu, S. Yang, H. Chen, and M. Chen, "Modulation bandwidth enhanced self-injection locking laser with an external high-Q microring reflector," Opt. Lett. **46**, 3251–3254 (2021). https://doi.org/10.1364/OL.432152
35. V. A. Gaisler, I. A. Derebezov, A. V. Gaisler, D. V. Dmitriev, A. I. Toropov, M. M. Kachanova, Yu. A. Zhivodkov, A. S. Kozhuhov, D. V. Scheglov, and A. V. Latyshev, "Subminiature light sources based on semiconductor nanostructures," Optoelectron., Instrum. Data Process. **56**, 518–526 (2020). https://doi.org/10.3103/S8756699020050052
36. L. Jiang, L. Shi, J. Luo, Q. Gao, M. Bai, T. Lan, P. I. Iroegbu, L. Dang, L. Huang, and T. Zhu, "Simultaneous self-injection locking of two VCSELs to a single whispering-gallery-mode microcavity," Opt. Express **29**, 37845–37851 (2021). https://doi.org/10.1364/OE.441595
37. V. V. Spirin, C. A. López-Mercado, S. I. Kablukov, E. A. Zlobina, I. O. Zolotovskiy, P. Mégret, and A. A. Fotiadi, "Single cut technique for adjustment of doubly resonant Brillouin laser cavities," Opt. Lett. **38**, 2528–2530 (2013). https://doi.org/10.1364/OL.38.002528
38. F. Wei, F. Yang, X. Zhang, D. Xu, M. Ding, L. Zhang, D. Chen, H. Cai, Z. Fang, and G. Xijia, "Subkilohertz linewidth reduction of a DFB diode laser using self-injection locking with a fiber Bragg grating Fabry-Perot cavity," Opt. Express **24**, 17406-17415 (2016). https://doi.org/10.1364/OE.24.017406
39. V. V. Spirin, C. A. López-Mercado, P. Mégret, and A. A. Fotiadi, "Single-mode Brillouin fiber laser passively stabilized at resonance frequency with self-injection locked pump laser," Laser Phys. Lett. **9**, 377 (2012). https://doi.org/10.7452/lapl.201110138
40. V. V. Spirin, C. A. López-Mercado, D. Kinet, P. Mégret, I. O. Zolotovskiy, and A. A. Fotiadi, "A single-longitudinal-mode Brillouin fiber laser passively stabilized at the pump resonance frequency with a dynamic population inversion grating," Laser Phys. Lett. **10**, 015102 (2013). https://doi.org/10.1088/1612-2011/10/1/015102
41. V. V. Spirin, M. Castro, C. A. López-Mercado, P. Mégret, and A. A. Fotiadi, "Optical locking of two semiconductor lasers through high-order Brillouin Stokes components in optical fiber," Laser Phys. **22**, 760–764 (2012). https://doi.org/10.1134/S1054660X12040214
42. C. E. Preda, A. A. Fotiadi, and P. Mégret, "Numerical approximation for Brillouin fiber ring resonator," Opt. Express **20**, 5783-5788 (2012). https://doi.org/10.1364/OE.20.005783
43. D. A. Korobko, I. O. Zolotovskii, V. V. Svetukhin, A. V. Zhukov, A. N. Fomin, C. V. Borisova, and A. A. Fotiadi, "Detuning effects in Brillouin ring microresonator laser," Opt. Express **28**, 4962–4972 (2020). https://doi.org/10.1364/OE.382357
44. C. A. López-Mercado, V. V. Spirin, J. L. Bueno Escobedo, A. Márquez Lucero, P. Mégret, I. O. Zolotovskii, and A. A. Fotiadi, "Locking of the DFB laser through fiber optic resonator on different coupling regimes," Opt. Commun. **359**, 195–199 (2016). https://doi.org/10.1016/j.optcom.2015.09.076
45. J. L. Bueno Escobedo, V. V. Spirin, C. A. López-Mercado, P. Mégret, I. O. Zolotovskii, and A. A. Fotiadi, "Self-injection locking of the DFB laser through an external ring fiber cavity: Polarization behavior," Results Phys. **6**, 59–60 (2016). https://doi.org/10.1016/j.rinp.2016.01.017
46. J. Geng, L. Yang, J. Liang, Sh. Liu, and Yo. Zhang, "Stability in self-injection locking of the DFB laser through a fiber optic resonator," Opt. Commun. **505**, 127531 (2022). https://doi.org/10.1016/j.optcom.2021.127531
47. D. A. Korobko, I. O. Zolotovskii, K. Panajotov, V. V. Spirin, and A. A. Fotiadi, "Self-injection-locking linewidth narrowing in a semiconductor laser coupled to an external fiber-optic ring resonator," Opt. Communications **405**, 253–258 (2017). https://doi.org/10.1016/j.optcom.2017.08.040
48. T. W. Hansch and B. Couillaud, "Laser frequency stabilization by polarization spectroscopy of a reflecting reference cavity," Opt. Communications **35**, 441–444 (1980). https://doi.org/10.1016/0030-4018(80)90069-3
49. J. Alnis, A. Matveev, N. Kolachevsky, Th. Udem, and T. W. Hänsch, "Subhertz linewidth diode lasers by stabilization to vibrationally and thermally compensated ultralow-expansion glass Fabry-Pérot cavities," Phys. Rev. A **77**, 053809 (2008). https://doi.org/10.1103/PhysRevA.77.053809
50. M. H. Idjadi and F. Aflatouni, "Integrated Pound–Drever–Hall laser stabilization system in silicon," Nat Commun. **8**, 1209 (2017). https://doi.org/10.1038/s41467-017-01303-y
51. D. Derickson, C. Hentschel, and J. Vobis, *Fiber Optic Test and Measurement* (Prentice Hall PTR, Upper Saddle River, N.J., 1998).
52. L. B. Mercer, "1 /f frequency noise effects on self-heterodyne linewidth measurements," IEEE Lightwave Technol. **9**, 485–493 (1991). https://doi.org/10.1109/50.76663
53. M. Chen, Z. Meng, J. Wang, and W. Chen, "Ultra-narrow linewidth measurement based on Voigt profile fitting," Opt. Express **23**, 6803–6808 (2015). https://doi.org/10.1364/OE.23.006803

54. E. Fomiryakov, D. Kharasov, S. Nikitin, O. Nanii, and V. Treshchikov, "New approach to laser characterization using delayed self-heterodyne interferometry," J. Lightwave Technol. **39**, 5191–5196 (2021). https://doi.org/10.1109/JLT.2021.3082263
55. Zh. Ou, X. Bao, Ya. Li, B. Saxena, and L. Chen, "Ultranarrow linewidth Brillouin fiber laser," IEEE Photonics Technol. Lett. **26**, 2058–2061 (2014). https://doi.org/10.1109/LPT.2014.2346783
56. I. S. Panyaev, P. A. Itrin, D. A. Korobko, and A. A. Fotiadi, "Self-trapping of frequency and stabilization of a narrowband generation of a semiconductor DFB laser in a circuit with external cavity on fiber with preservation of polarization," in *X Int. Workshop on Fiber Lasers, Novosibirsk, 2022*, pp. 184–185.
57. A. H. Hartog, *An Introduction to Distributed Optical Fibre Sensors*, Series in Fiber Optic Sensors (CRC Press, Boca Raton, Fla., 2017). https://doi.org/10.1201/9781315119014
58. Y. Lu, T. Zhu, L. Chen, and X. Bao, "Distributed vibration sensor based on coherent detection of phase-OTDR," J. Lightwave Technol. **28**, 3243–3249 (2010).
59. F. Peng, H. Wu, X.-H. Jia, Yu.-J. Rao, Z.-N. Wang, and Zh.-P. Peng, "Ultra-long high-sensitivity Φ-OTDR for high spatial resolution intrusion detection of pipelines," Opt. Express **22**, 13804–13810 (2014). https://doi.org/10.1364/OE.22.013804
60. B. G. Gorshkov, K. Yüksel, A. A. Fotiadi, M. Wuilpart, D. A. Korobko, A. A. Zhirnov, K. V. Stepanov, A. T. Turov, Yu. A. Konstantinov, and I. A. Lobach, "Scientific applications of distributed acoustic sensing: State-of-the-art review and perspective," Sensors **22**, 1033 (2022). https://doi.org/10.3390/s22031033
61. A. V. Faustov, A. V. Gusarov, P. Megret, M. Wuilpart, A. V. Zhukov, S. G. Novikov, V. V. Svetukhin, and A. A. Fotiadi, "The use of optical frequency-domain reflectometry in remote distributed measurements of the γ-radiation dose," Tech. Phys. Lett. **41**, 414–417 (2015). 10.1134/S1063785015050053
62. A. V. Faustov, A. V. Gusarov, P. Mégret, M. Wuilpart, A. V. Zhukov, S. G. Novikov, V. V. Svetukhin, and A. A. Fotiadi, "Application of phosphate doped fibers for OFDR dosimetry," Results Phys. **6**, 86–87 (2016). https://doi.org/10.1016/j.rinp.2016.02.001
63. L. Rossi, D. Marini, F. Bastianini, and G. Bolognini, "Analysis of enhanced-performance fibre Brillouin ring laser for Brillouin sensing applications," Opt. Express **27**, 29448–29459 (2019). https://doi.org/10.1364/OE.27.029448
64. D. Marini, M. Iuliano, F. Bastianini, and G. Bolognini, "BOTDA sensing employing a modified Brillouin fiber laser probe source," J. Lightwave Technol. **36**, 1131–1137 (2018). https://doi.org/10.1109/JLT.2017.2772326
65. L. Rossi, F. Bastianini, and G. Bolognini, "Study of injection-locked stabilized, short cavity Brillouin ring laser source design for fiber sensing applications," J. Eur. Opt. Soc. Rapid Publ. **18**, 5 (2022). https://doi.org/10.1051/jeos/2022005
66. M. A. Soto, "Distributed Brillouin sensing: Time-domain techniques," in *Handbook of Optical Fibers* (Springer, Singapore, 2018), pp. 1663–1753. https://doi.org/10.1007/978-981-10-7087-7_7

Translated by I. Obrezanova