

Stabilizing Brillouin fiber laser for applications in distributed BOTDA sensing

V. V. Spirin^a, C. A. Lopez-Mercado^a, P. Mégret^b,
D. A. Korobko^c, I. O. Zolotovskii^c, A. A. Fotiadi^{b,c,d}

^aCentro de Investigación Científica y de Educación Superior de Ensenada,
Carretera Ensenada-Tijuana No.3918, Zona Playitas, 22860 Ensenada, B.C., Mexico.

^bUniversity of Mons, Boulevard Dolez 31, 7000 Mons, Belgium.

^cUlyanovsk State University, 42 Leo Tolstoy Street, Ulyanovsk, 432970, Russia.

^dIoffe Physico-Technical Institute of the RAS, 26 Polytekhnicheskaya Street,
St. Petersburg 194021, Russia.

ABSTRACT

Self-injection locking to an external fiber cavity is an efficient technique enabling drastic linewidth narrowing and self-stabilization of semiconductor lasers. We introduce a simple dual-frequency laser that employs the same external ring fiber cavity for self-injection locking of a standard semiconductor DFB laser and for the generation of the Stokes light via stimulated Brillouin scattering. In contrast to the previous Brillouin laser configurations, the system spliced from standard telecom components is supplied by a low-bandwidth active optoelectronic feedback that helps to maintain the self-injection locking to provide both the DFB laser line narrowing and permanent coupling between the DFB laser and the fiber ring cavity thus enabling the dual-frequency laser operation. The laser performance characteristics are well superior to the on-board laser modules commonly used with BOTDA. In particular, the configuration reduces the natural Lorentzian linewidth of the light emitted by the laser at pump and Stokes frequencies down to 270 Hz and 110 Hz, respectively, and features a stable 300-Hz-width RF spectrum characterizing beating between two laser outputs. In a direct comparison with the commercial BOTDA, we explore the utilization of our low-cost solution for the BOTDA sensing demonstrating distributed measurements of the Brillouin frequency shift in 10-km sensing fiber with 1.5m spatial resolution.

Keywords: Brillouin distributed sensing; self-injection locking; fiber ring cavity; Brillouin lasers.

1. INTRODUCTION

A global market of fiber optic monitoring systems is booming. A significant part of this market is accounted for by distributed monitoring systems based on the Rayleigh and Brillouin scatterings [1-19]. A key and most expensive part of such a system is the master-oscillator modules producing interrogating optical signals with rather specific performance characteristics and stringent requirements to the laser stability. Too high cost and complexity of such laser modules hinder many potential applications of the distributed fiber sensors in a large volume market, where highly performed, but cost-efficient sensors are urgently demanded. Therefore, new technical solutions reducing the cost of the interrogating lasers [20-35] while maintaining their full functionality is of great practical importance for new sensor applications, in particular, in distributed sensor networks for utility service implementing the smart city concept. Although current progress in the field of low-noise lasers is associated with the use of microcavities, the robust and compact laser sources based on the whispering gallery modes are still very complicated in fabrication and, therefore, too expensive for widespread use. In this context, their cheaper alternatives represented by simple fiber-optics spliced configurations are of strong demand.

In 2012 we have demonstrated a kHz-linewidth laser just combining a standard DFB laser diode and a few passive telecommunication components [36-43]. The principle of operation employs the mechanism of self-injection locking that significantly improves the DFB laser performance [43-47]. While a typical linewidth of free-running DFB semiconductor lasers ranges from a few to tens MHz, self-injection locking of the DFB laser through an external fiber

ring cavity causes a drastic reduction of the laser linewidth down to a few kHz making it attractive for applications in distributed sensing. Once getting locking to the ring cavity mode, the laser starts to generate the cavity resonant frequency. Then any slow change of the ring mode frequency (due to environment temperature fluctuations, for example) causes the same change of the laser frequency. However, the main drawback of this technique is high sensitivity of the lasing to fluctuations of the configuration parameters and surroundings that causes rare mode-hopping events. In the experiment, a stable laser operation is commonly observed for a few seconds making laser applications for distributed sensing rather questionable. Nevertheless, the applicability of the proposed laser solution for phase-OTDR sensing has been verified experimentally. In our testing experiments the standard on-board ~ 100 -Hz-linewidth laser module in the phase-OTDR analyzer has been replaced by our low-cost self-injection locked laser demonstrating no degradation of the system performance for detection and localization of the vibrations in 10-km-long fiber and for restoration of the vibration spectrum (300-5600 Hz) in 4-km fiber [48-51].

In this paper we explore the potential of the low-cost self-injection locked laser solution for operation with BOTDA sensing [52-64] highlighting its ability to replace the standard on-board laser module in the Brillouin analyzer. In our laser configuration the same ring fiber cavity is used to generate narrow-band light at the pump frequency (through self-injection locking mechanism) and narrow-band laser light at Stokes frequency (through stimulated Brillouin scattering). Although the fiber ring cavity is commonly used to generate Brillouin wave from an external laser diode [65-69], the maintaining coupling between the DFB laser and a high-Q ring fiber cavity always remains a technically complicated and cost consuming task. In our approach, the implementation of the self-injection locking mechanism into the Brillouin ring fiber laser helps to maintain coupling between the DFB laser and the external fiber cavity enabling dual-frequency laser operation [70, 71]. The laser system is supplied by a simplest low-bandwidth active optoelectronic feedback circuit controlled by a low-cost USB-DAQ card. Importantly, a stable operation of two frequencies mutually locked to the Brillouin resonance is provided by the self-injection locking mechanism, while the active feedback loop is used just to support this regime. Therefore, in terms of feedback circuit bandwidth, complexity, and allocated memory, the used electronics is much less consuming than optoelectronic systems commonly used with fiber lasers [72, 73]. We present results of the testing experiments characterizing the use of the self-injection locked Brillouin laser configuration for distributed measurements of the Brillouin frequency shifts over 10 km with the spatial resolution of 1.5 m. Importantly, the same measurements have been performed with the use of the commercial BOTDA (OZ-optics, Inc.) at the same settings and applied to the same testing line. A direct comparison of the results highlights no degradation of the BOTDA system performance associated with the use of its low-cost home-made analogue.

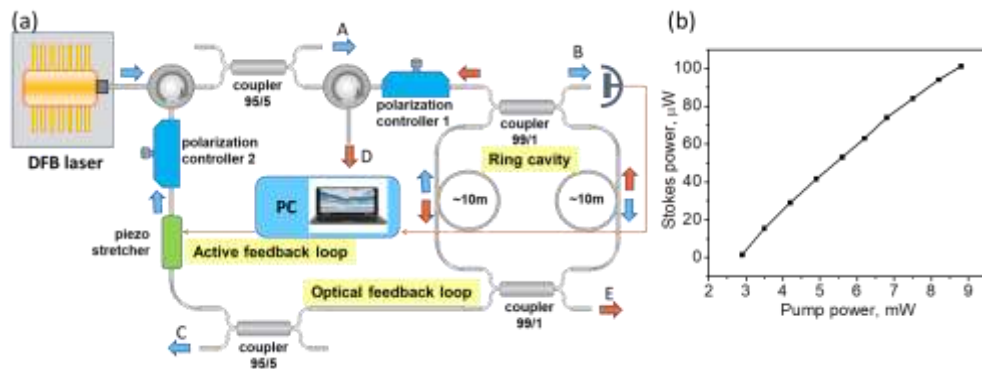


Fig. 1. (a) The experimental laser configuration; (b) Brillouin output power (port D) as a function of the DFB laser power.

2. DUAL-FREQUENCY LASER

We have evaluated the performance of a BOTDA system using the low-cost self-injection locked DFB laser as a dual-frequency master oscillator [71]. The experimental configuration of the a dual-frequency master oscillator is shown in Fig.1. The principle of the laser operation is explained in our recent publications. The dual-frequency laser performance is quite impressive considering that no significant attempt has been made to temperature stabilize the set-up. It emits two narrow-band laser lines at pump and Stokes frequencies spaced by ~ 11 GHz and delivered through two linear polarized fiber outputs. The laser operation frequencies are strongly locked to the ring cavity resonances and their drift measured

in the experiment (~ 8.8 MHz/min) is mainly determined by environmental temperature variations. The laser output powers are ~ 9 mW and ~ 100 μ W for pump and Stokes outputs, respectively. Further power scaling is provided with external EDFA amplifiers. The laser performance characteristics measured with methods [74-77] are summarized in Fig.2.

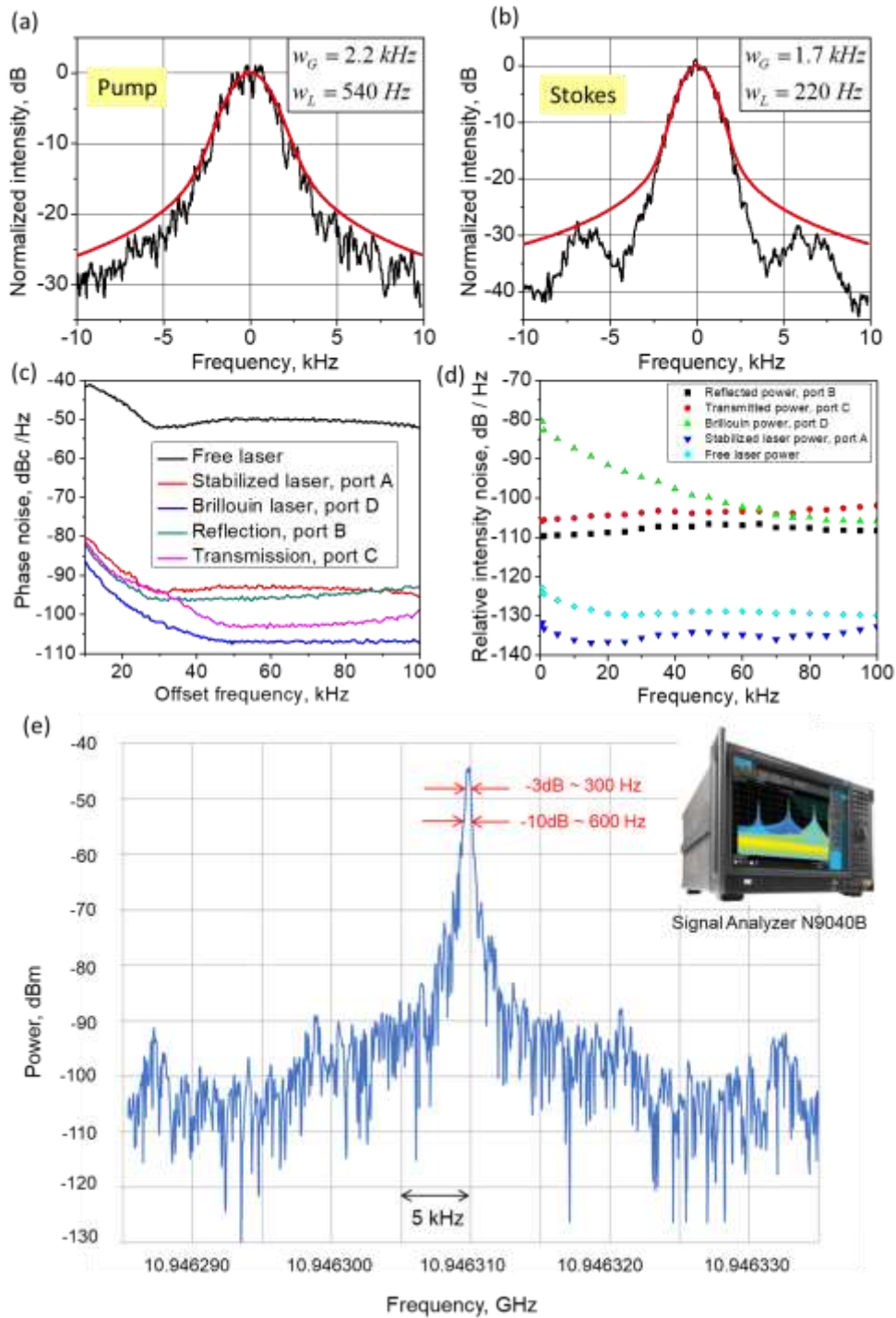


Fig. 2. Dual-frequency laser performance: self-heterodyne spectra (a, b), phase noise (c), relative intensity noise (d) and RF pump-to-Stokes beating spectrum (e).

The pump and Stokes laser outputs are characterized by the power of 10mW and 50μW and natural Lorenz linewidths of ~270 Hz and ~110 Hz, respectively. The laser noise characteristics are on the level of more expensive laser counterparts. The beating between two laser outputs features a stable RF spectrum with 300-Hz-linewidth and peak strongly locked to the Brillouin resonance in the laser cavity fiber [Fig.2] ($\nu_{p0} - \nu_{s0} = \Delta_{SBS}$, where Δ_{SBS} is the Brillouin frequency shift). The demonstrated laser performance is well superior to the specifications of on-board laser modules commonly used with commercial BOTDAs.

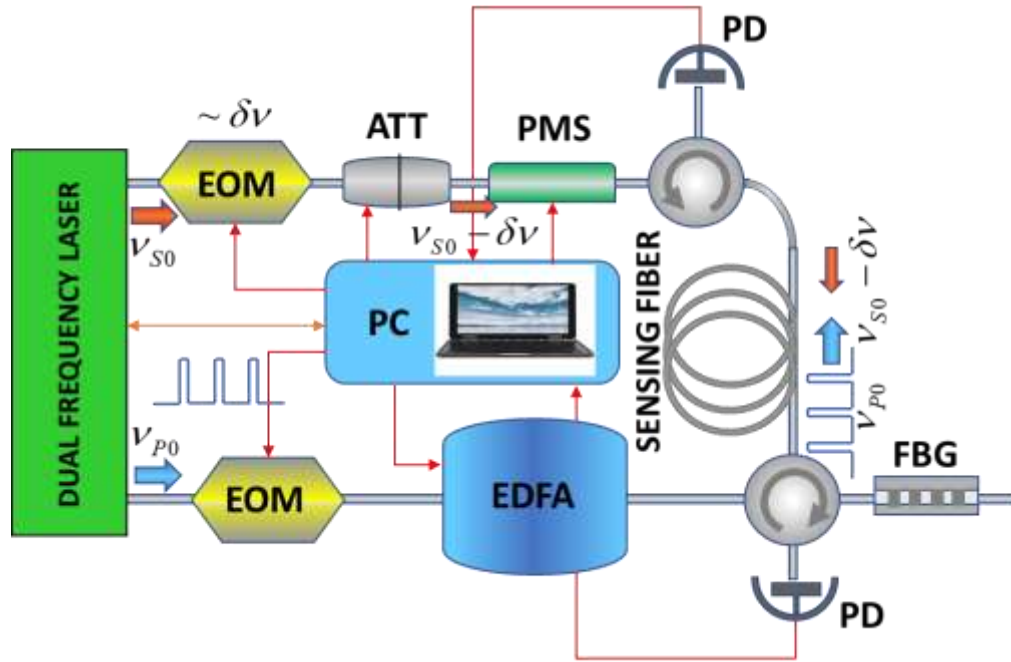


Fig. 3. The configuration of the lost-efficient BOTDA system

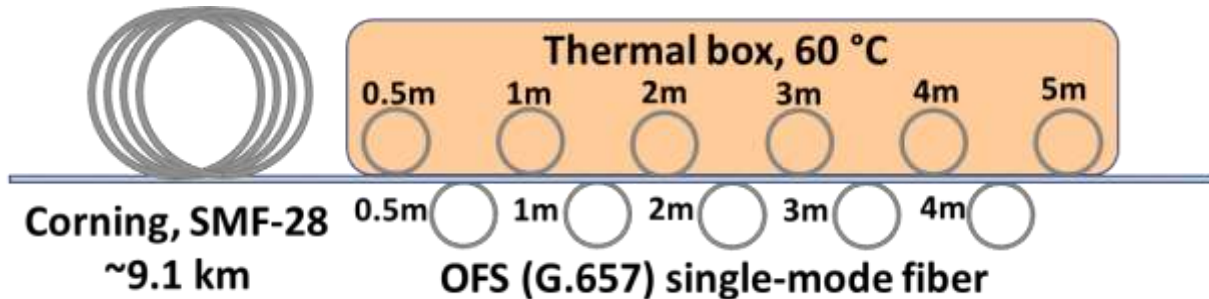


Fig. 4. The used fiber-optics testing line.

3. LASER OPERATION WITH BOTDA

The BOTDA experimental configuration depicted in Fig. 3 is based on a simple modification of the classical pump and probe set-up. It employs two counter-propagating optical waves, a pump pulsed light and a continuous probe wave. The laser generates highly coherent light at pump (ν_{p0}) and Stokes (ν_{s0}) frequencies delivered through pump and probe channels, respectively. The laser radiation emitted at the pump frequency ν_{p0} is passed through the electro-optical intensity modulators (EOM) and Erbium-doped fiber amplifier (EDFA) forming a periodic train of rectangular pump pulses with the peak power of ~300 mW, pulse duration of ~15 ns and repetition rate of ~10 kHz. The laser radiation at

the Stokes frequency ν_{s0} passes the single-side band electro-optic modulator (EOM) driven at the frequency $\delta\nu_s$, electrically controllable optical attenuator and polarization scrambler forming a $\sim 10\mu\text{W}$ cw probe signal with sidebands at frequencies $\nu_s = \nu_{s0} - \delta\nu_s$ tunable over the whole EOM bandwidth with change of $\delta\nu_s$ ($< 1.5\text{GHz}$). The pump pulses at ν_{L0} and cw probe signal at ν_s are introduced into the sensing fiber line from opposite fiber ends. Brillouin interaction of contra-propagating optical fields inside the fiber causes an energy transfer from the pump pulse to the Stokes signal leading to a specific modulation of the probe signal recorded by the fast photodetector and PC acquisition card at the fiber output. The modulation amplitude (typically $< 100\text{nW}$) is proportional to the local Brillouin gain at the fiber point, where interaction of the probe signal with the pump pulse has occurred. The recorded traces of the probe signal averaged over 4096 realizations (pump pulses) are used to restore distribution of the Brillouin gain along the fiber. The traces recorded at different $\delta\nu_s$ are used to map the Brillouin gain spectrum in each fiber point with a spatial resolution of $\sim 1.5\text{m}$ corresponding to the pump pulse duration of $\sim 15\text{ns}$.

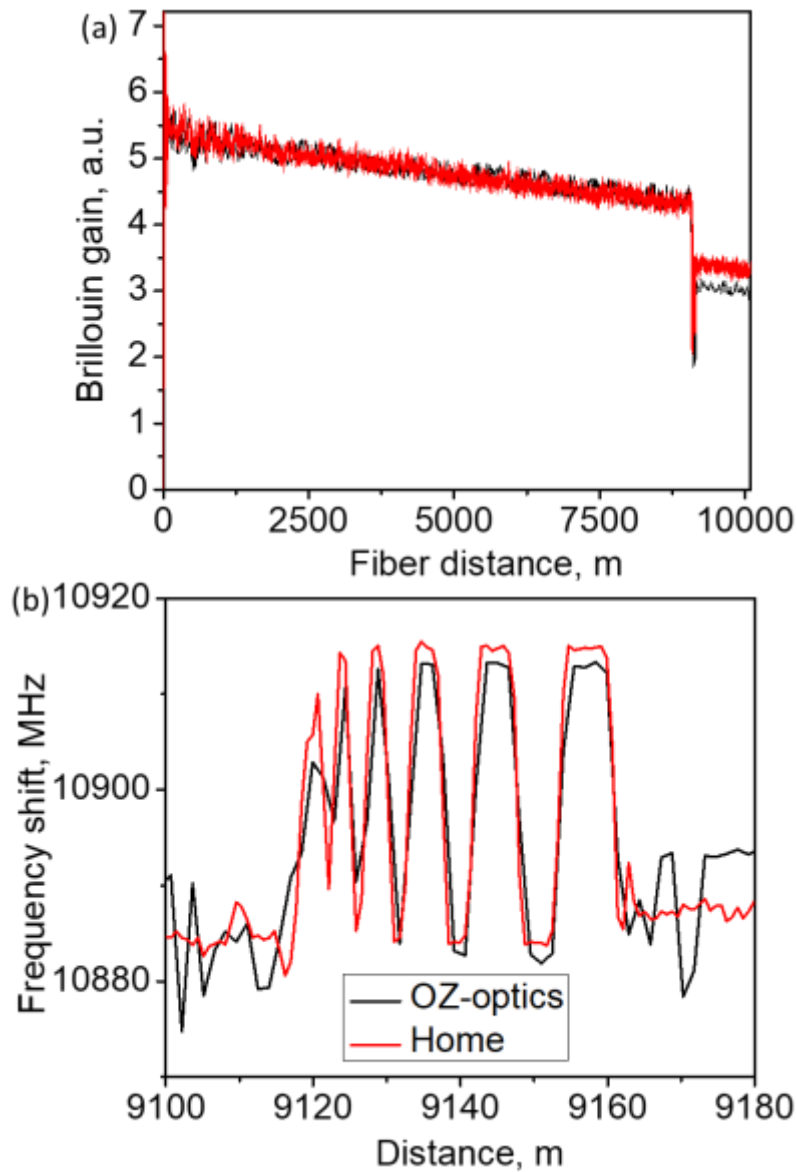


Fig. 5. BOTDA traces at the fixed frequency difference (a) and distribution of the Brillouin frequency shift (b) obtained with the commercial (black) and home (red) analyzers.

To evaluate the BOTDA performance, we built a special fiber testing line similar to that commonly used for specification and calibration of commercial BOTDAs. The testing line of 10 km length has been built from the SMF-28 Corning fiber (9.1 km) spliced with OFS (G.657) fiber and comprises several altered coiled fiber segments of different length (0.5-4.0 m) kept at different temperatures. Even coils are placed into a heat chamber thermostabilized at 60 °C, while odd are rested at room temperature (~20 °C) as well as almost the whole length of the fiber [see, Fig.4]. The same testing experiments have been performed simultaneously with the tested BOTDA and with the commercial BOTDA system (OZ-optics). The results of the experiments are presented in Fig.5.

First, we have adjusted the frequency difference between the pump and probe signal to the Brillouin frequency shift corresponding to the standard SMS-28 fiber at room temperature. Fig.5(a) compares the averaged probe signal trace with the similar trace obtained with the commercial BOTDA. Both traces possess similar behavior, including features of the signal modulation pronounced in points with a different Brillouin frequency shift. The distribution of the peak spectrum frequency along the fiber segments possessing different temperatures is shown in Fig.5 (b) with a step of ~2 MHz. One can see that the quality of restoration is rather high. Although the restored spectrum is slightly noisier than one obtained with the commercial BOTDA, it well reproduces all specific features of the real spectrum and allows perfect determination of its peak position and amplitude both important for Brillouin sensing. Both devices give almost the same distribution providing a good agreement in absolute peak frequencies and its position, all peaks are well resolved. The spatial resolution corresponds to the value of 1.5 m determined by the pulse duration. One can see, that our experimental device provides even better spatial resolution than the commercial BOTDA with the same pulse duration.

4. CONCLUSION

In conclusion, we have introduced a simple dual-frequency laser based on a DFB laser coupled to an all-fiber ring cavity and working in self-injection-locking regime. In our laser configuration, the same ring fiber cavity is exploited both for self-injection locking of the DFB laser and for generation of Stokes light via stimulated Brillouin scattering. A low-cost USB-DAQ is used to stabilize the system preventing mode-hopping. Importantly, a stable laser operation at two mutually locked frequencies is provided by the self-injection locking mechanism, while the active feedback loop just helps the laser to operate in this regime. Besides, the self-injection locking mechanism maintains permanent coupling between the DFB laser and the external fiber ring cavity enabling perfect resonant pumping for low-noise Brillouin lasing. The reported laser characteristics are well superior to the requirements to the laser modules commonly used with Brillouin Optical Time Domain Analyzer (BOTDA). In a direct comparison with the commercial BOTDA, we have explored the utilization of our low-cost solution for the BOTDA sensing demonstrating distributed measurements of the Brillouin frequency shift in 10-km sensing fiber with 1.5m spatial resolution. No degradation of the system performance characteristics associated with the use of the low-cost laser module instead of the on-board solution is found.

ACKNOWLEDGEMENTS

The work on the system design and characterization was supported by the Ministry of Higher Education and Science of the Russian Federation (Megagrant Program, project # 2020-220-08-1369). The construction of the home-made BOTDA system was supported by the Russian Fund of Basic Research (19-42-730009 p_a). The work on the laser application in Brillouin reflectometry and special amplifiers was supported by the Russian Science Foundation (project 18-12-00457).

REFERENCES

- [1] Udd E., Spillman W.B., Jr., [Fiber Optic Sensors: An Introduction for Engineers and Scientists]. 2nd ed. John Wiley & Sons; Hoboken, NJ, USA (2011).
- [2] Barrias, A., Casas, J. and Villalba, S., "A Review of Distributed Optical Fiber Sensors for Civil Engineering Applications," Sensors 16(5), 748 (2016).

- [3] Galindez-Jamioy, C. A. and López-Higuera, J. M., “Brillouin Distributed Fiber Sensors: An Overview and Applications,” *Journal of Sensors* 2012, 1–17 (2012).
- [4] Bao X., Chen L., “Recent Progress in Distributed Fiber Optic Sensors,” *Sensors*, 12(7), 8601–8639 (2012).
- [5] Eggleton, B. J., Poulton, C. G., Rakich, P. T., Steel, M. J. and Bahl, G., “Brillouin integrated photonics,” *Nature Photonics* 13(10), 664–677 (2019).
- [6] Li, J., Suh, M.-G. and Vahala, K., “Microresonator Brillouin gyroscope,” *Optica* 4(3), 346 (2017).
- [7] Marpaung, D., Yao, J. and Capmany, J., “Integrated microwave photonics,” *Nature Photonics* 13(2), 80–90 (2019).
- [8] Faustov, A. V., Gusarov, A. V., Mégret, P., Wuilpart, M., Zhukov, A. V., Novikov, S. G., Svetukhin, V. V. and Fotiadi, A. A., “The use of optical frequency-domain reflectometry in remote distributed measurements of the γ -radiation dose,” *Technical Physics Letters* 41(5), 414–417 (2015).
- [9] Faustov, A. V., Gusarov, A. V., Mégret, P., Wuilpart, M., Zhukov, A. V., Novikov, S. G., Svetukhin, V. V. and Fotiadi, A. A., “Application of phosphate doped fibers for OFDR dosimetry,” *Results in Physics* 6, 86–87 (2016).
- [10] Faustov, A. V., Gusarov, A., Wuilpart, M., Fotiadi, A. A., Liokumovich, L. B., Zolotovskiy, I. O., Tomashuk, A. L., de Schoutheete, T. and Megret, P., “Comparison of Gamma-Radiation Induced Attenuation in Al-Doped, P-Doped and Ge-Doped Fibres for Dosimetry,” *IEEE Transactions on Nuclear Science* 60(4), 2511–2517 (2013).
- [11] Faustov, A. V., Gusarov, A., Liokumovich, L. B., Fotiadi, A. A., Wuilpart, M. and Mégret, P., “Comparison of simulated and experimental results for distributed radiation-induced absorption measurement using OFDR reflectometry,” *Fifth European Workshop on Optical Fibre Sensors*, L. R. Jaroszewicz, Ed., *Proceedings of the SPIE* 8794, 87943O (2013).
- [12] Morana, A., Planes, I., Girard, S., Cangialosi, C., Delepine-Lesoille, S., Marin, E., Boukenter, A. and Ouerdane, Y., “Steady-State Radiation-Induced Effects on the Performances of BOTDA and BOTDR Optical Fiber Sensors,” *IEEE Transactions on Nuclear Science* 65(1), 111–118 (2018).
- [13] Fotiadi, A. A., Brambilla, G., Ernst, T., Slattery, S. A. and Nikogosyan, D. N., “TPA-induced long-period gratings in a photonic crystal fiber: inscription and temperature sensing properties,” *Journal of the Optical Society of America B* 24(7), 1475 (2007).
- [14] Caucheteur, C., Fotiadi, A., Megret, P., Slattery, S. A. and Nikogosyan, D. N., “Polarization properties of long-period gratings prepared by high-intensity femtosecond 352-nm pulses,” *IEEE Photonics Technology Letters* 17(11), 2346–2348 (2005).
- [15] Dong, Y., Jiang, T., Teng, L., Zhang, H., Chen, L., Bao, X. and Lu, Z., “Sub-MHz ultrahigh-resolution optical spectrometry based on Brillouin dynamic gratings,” *Optics Letters* 39(10), 2967 (2014).
- [16] Yuelan Lu, Tao Zhu, Liang Chen and Xiaoyi Bao., “Distributed Vibration Sensor Based on Coherent Detection of Phase-OTDR,” *Journal of Lightwave Technology* (2010).
- [17] Muanenda, Y., Oton, C. J., Faralli, S. and Di Pasquale, F., “A Cost-Effective Distributed Acoustic Sensor Using a Commercial Off-the-Shelf DFB Laser and Direct Detection Phase-OTDR,” *IEEE Photonics Journal* 8(1), 1–10 (2016).
- [18] Xu, S., Qin, Z., Zhang, W. and Xiong, X., “Monitoring Vehicles on Highway by Dual-Channel ϕ -OTDR,” *Applied Sciences* 10(5), 1839 (2020).
- [19] Zhong, X., Zhao, S., Deng, H., Gui, D., Zhang, J. and Ma, M., “Nuisance alarm rate reduction using pulse-width multiplexing Φ -OTDR with optimized positioning accuracy,” *Optics Communications* 456, 124571 (2020).
- [20] Yang, Z., Li, C., Xu, S. and Yang, C., [Single-Frequency Fiber Lasers], Springer Singapore (2019).
- [21] Popov, S. M., Chamorovski, Y. K., Isaev, V. A., Mégret, P., Zolotovskii, I. O. and Fotiadi, A. A., “Electrically tunable Brillouin fiber laser based on a metal-coated single-mode optical fiber,” *Results in Physics* 7, 852–853 (2017).
- [22] Popov, S. M., Butov, O. V., Chamorovskiy, Y. K., Isaev, V. A., Kolosovskiy, A. O., Voloshin, V. V., Vorob’ev, I. L., Vyatkin, M. Y., Mégret, P., Odnoblyudov, M., Korobko, D. A., Zolotovskii, I. O. and Fotiadi, A. A., “Brillouin lasing in single-mode tapered optical fiber with inscribed fiber Bragg grating array,” *Results in Physics* 9, 625–627 (2018).
- [23] Popov, S. M., Butov, O. V., Chamorovski, Y. K., Isaev, V. A., Mégret, P., Korobko, D. A., Zolotovskii, I. O. and Fotiadi, A. A., “Narrow linewidth short cavity Brillouin random laser based on Bragg grating array fiber and dynamical population inversion gratings,” *Results in Physics* 9, 806–808 (2018).

- [24] Popov, S. M., Butov, O. V., Bazakutsa, A. P., Vyatkin, M. Y., Chamorovskii, Y. K. and Fotiadi, A. A., "Random lasing in a short Er-doped artificial Rayleigh fiber," *Results in Physics* 16, 102868 (2020).
- [25] Popov, S. M., Butov, O. V., Kolosovskii, A. O., Voloshin, V. V., Vorob'ev, I. L., Isaev, V. A., Vyatkin, M. Y., Fotiadi, A. A. and Chamorovsky, Y. K., "Optical fibres and fibre tapers with an array of Bragg gratings," *Quantum Electronics* 49(12), 1127–1131 (2019).
- [26] Boivinet, S., Lecourt, J.-B., Hernandez, Y., Fotiadi, A. A., Wuilpart, M. and Megret, P., "All-Fiber 1- μ m PM Mode-Lock Laser Delivering Picosecond Pulses at Sub-MHz Repetition Rate," *IEEE Photonics Technology Letters* 26(22), 2256–2259 (2014).
- [27] Kuznetsov, M. S., Antipov, O. L., Fotiadi, A. A. and M egret, P., "Electronic and thermal refractive index changes in Ytterbium-doped fiber amplifiers," *Optics Express* 21(19), 22374 (2013).
- [28] Phan Huy, K., Nguyen, A. T., Brainis, E., Haelterman, M., Emplit, P., Corbari, C., Canagasabay, A., Kazansky, P. G., Deparis, O., Fotiadi, A. A., M egret, P. and Massar, S., "Photon pair source based on parametric fluorescence in periodically poled twin-hole silica fiber," *Optics Express* 15(8), 4419 (2007).
- [29] H. J. Khashi, S. V. Sergeev, M. Al-Araimi, A. Rozhin, D. Korobko, and A. Fotiadi, "High-frequency vector harmonic mode locking driven by acoustic resonances," *Optics Letters* 44, 5112-5115 (2019).
- [30] Lobach, I. A., Drobyshev, R. V., Fotiadi, A. A., Podivilov, E. V., Kablukov, S. I. and Babin, S. A., "Open-cavity fiber laser with distributed feedback based on externally or self-induced dynamic gratings," *Opt. Lett.* 42(20), 4207 (2017).
- [31] Gruk, D.A., Kurkov, A.S., Razdobreev, I.M., Fotiadi A.A., "Self-Q-switched ytterbium-doped cladding-pumped fibre laser," *Quantum Electronics* 32(11) 1017-1019 (2002)
- [32] Fotiadi, A. A., Kurkov, A. S., & Razdobreev, I. M. (2007, May). Dynamics of all-fiber self-Q-switched ytterbium/samarium laser. In *Conference on Lasers and Electro-Optics* (p. CMC4). Optical Society of America.
- [33] Korobko, D. A., Fotiadi, A. A. and Zolotovskii, I. O., "Mode-locking evolution in ring fiber lasers with tunable repetition rate," *Opt. Express* 25(18), 21180 (2017).
- [34] Lobach, I. A., Kablukov, S. I., Podivilov, E. V., Fotiadi, A. A. and Babin, S. A., "Fourier synthesis with single-mode pulses from a multimode laser," *Opt. Lett.* 40(15), 3671 (2015).
- [35] Fotiadi, A. A., Antipov, O. L., & M egret, P. (2010). Resonantly induced refractive index changes in Yb-doped fibers: the origin, properties and application for all-fiber coherent beam combining. *Frontiers in Guided Wave Optics and Optoelectronics*, 209-234
- [36] Spirin, V. V., Castro, M., L opez-Mercado, C. A., M egret, P. and Fotiadi, A. A., "Optical locking of two semiconductor lasers through high-order Brillouin Stokes components in optical fiber," *Laser Physics* 22(4), 760–764 (2012).
- [37] Korobko, D. A., Zolotovskii, I. O., Panajotov, K., Spirin, V. V. and Fotiadi, A. A., "Self-injection-locking linewidth narrowing in a semiconductor laser coupled to an external fiber-optic ring resonator," *Optics Communications* 405, 253–258 (2017).
- [38] Spirin, V. V., L opez-Mercado, C. A., M egret, P. and Fotiadi, A. A., "Single-mode Brillouin fiber laser passively stabilized at resonance frequency with self-injection locked pump laser," *Laser Physics Letters* 9(5), 377–380 (2012).
- [39] Spirin, V. V., L opez-Mercado, C. A., Kinet, D., M egret, P., Zolotovskiy, I. O. and Fotiadi, A. A., "A single-longitudinal-mode Brillouin fiber laser passively stabilized at the pump resonance frequency with a dynamic population inversion grating," *Laser Phys. Lett.* 10(1), 015102 (2012)
- [40] Bueno Escobedo, J. L., Spirin, V. V., L opez-Mercado, C. A., M egret, P., Zolotovskii, I. O. and Fotiadi, A. A., "Self-injection locking of the DFB laser through an external ring fiber cavity: Polarization behavior," *Results in Physics* 6, 59–60 (2016).
- [41] L opez-Mercado, C. A., Spirin, V. V., Bueno Escobedo, J. L., M arquez Lucero, A., M egret, P., Zolotovskii, I. O. and Fotiadi, A. A., "Locking of the DFB laser through fiber optic resonator on different coupling regimes," *Optics Communications* 359, 195–199 (2016).
- [42] Spirin, V.V., M egret, P., Fotiadi, A.A., "Passively Stabilized Doubly Resonant Brillouin Fiber Lasers," in *Fiber Lasers*, edited by M. Paul, J. Kolkata, INTECH 2016.
- [43] Petermann, K., [*Laser Diode Modulation and Noise*], Springer Netherlands (1988).

- [44] Ohtsubo, J., [Semiconductor Lasers], Springer Berlin Heidelberg (2013).
- [45] Galiev, R. R., Pavlov, N. G., Kondratiev, N. M., Koptyaev, S., Lobanov, V. E., Voloshin, A. S., Gorodnitskiy, A. S. and Gorodetsky, M. L., "Spectrum collapse, narrow linewidth, and Bogatov effect in diode lasers locked to high-Q optical microresonators," *Optics Express* 26(23), 30509 (2018).
- [46] Liang, W., Ilchenko, V. S., Eliyahu, D., Savchenkov, A. A., Matsko, A. B., Seidel, D. and Maleki, L., "Ultralow noise miniature external cavity semiconductor laser," *Nature Communications* 6(1) (2015).
- [47] Wei, F., Yang, F., Zhang, X., Xu, D., Ding, M., Zhang, L., Chen, D., Cai, H., Fang, Z. and Xijia, G., "Subkilohertz linewidth reduction of a DFB diode laser using self-injection locking with a fiber Bragg grating Fabry-Perot cavity," *Optics Express* 24(15), 17406 (2016).
- [48] Bueno Escobedo, J. L., Spirin, V. V., López-Mercado, C. A., Márquez Lucero, A., Mégret, P., Zolotovskii, I. O. and Fotiadi, A. A., "Self-injection locking of the DFB laser through an external ring fiber cavity: Application for phase sensitive OTDR acoustic sensor," *Results in Physics* 7, 641–643 (2017).
- [49] Spirin, V.V., Lopez-Mercado, C. A., Mégret, P., Fotiadi, A.A. "Fiber Laser for Phase-Sensitive Optical Time-Domain Reflectometry," in *Selected Topics on Optical Fiber Technologies and Applications*, edited by Fei Xu and Chengbo Mou, INTECH 2018.
- [50] Jason, J., Popov, S. M., Butov, O. V., Chamorovskii, Y. K., Golant, K. M., Fotiadi, A. A. and Wuilpart, M., "Sensitivity of high Rayleigh scattering fiber in acoustic/vibration sensing using phase-OTDR," *Optical Sensing and Detection V*, F. Berghmans and A. G. Mignani, Eds., Proc. SPIE (2018).
- [51] Bueno Escobedo, J. L., Jason, J., López-Mercado, C. A., Spirin, V. V., Wuilpart, M., Mégret, P., Korobko, D. A., Zolotovskiy, I. O. and Fotiadi, A. A., "Distributed measurements of vibration frequency using phase-OTDR with a DFB laser self-stabilized through PM fiber ring cavity," *Results in Physics* 12, 1840–1842 (2019)
- [52] Bao, X. and Chen, L., "Recent Progress in Brillouin Scattering Based Fiber Sensors," *Sensors* 11(4), 4152–4187 (2011).
- [53] Dong, Y., Zhang, H., Lu, Z., Chen, L. and Bao, X., "Long-Range and High-Spatial-Resolution Distributed Birefringence Measurement of a Polarization-Maintaining Fiber Based on Brillouin Dynamic Grating," *Journal of Lightwave Technology* 31(16), 2681–2686 (2013).
- [54] Angulo-Vinuesa, X., Dominguez-Lopez, A., Lopez-Gil, A., Ania-Castanon, J. D., Martin-Lopez, S. and Gonzalez-Herraez, M., "Limits of BOTDA Range Extension Techniques," *IEEE Sensors Journal* 16(10), 3387–3395 (2016).
- [55] Spirin, V. V., Kellerman, J., Swart, P. L. and Fotiadi, A. A., "Intensity noise in SBS with injection locking generation of Stokes seed signal," *Optics Express* 14(18), 8328 (2006).
- [56] Denisov, A., Soto, M. A. and Thévenaz, L., "Going beyond 1000000 resolved points in a Brillouin distributed fiber sensor: theoretical analysis and experimental demonstration," *Light: Science & Applications* 5(5), e16074–e16074 (2016).
- [57] Antman, Y., Primerov, N., Sancho, J., Thevenaz, L. and Zadok, A., "Localized and stationary dynamic gratings via stimulated Brillouin scattering with phase modulated pumps," *Optics Express* 20(7), 7807 (2012).
- [58] Peled, Y., Motil, A., Kressel, I. and Tur, M., "Monitoring the propagation of mechanical waves using an optical fiber distributed and dynamic strain sensor based on BOTDA," *Optics Express* 21(9), 10697 (2013).
- [59] Zadok, A., Antman, Y., Primerov, N., Denisov, A., Sancho, J. and Thevenaz, L., "Random-access distributed fiber sensing," *Laser & Photonics Reviews* 6(5), L1–L5 (2012).
- [60] Motil, A., Bergman, A. and Tur, M., "[INVITED] State of the art of Brillouin fiber-optic distributed sensing," *Optics & Laser Technology* 78, 81–103 (2016).
- [61] Sovran, I., Motil, A. and Tur, M., "Frequency-Scanning BOTDA With Ultimately Fast Acquisition Speed," *IEEE Photonics Technology Letters* 27(13), 1426–1429 (2015).
- [62] Tur, M., Motil, A., Sovran, I. and Bergman, A., "Recent progress in distributed Brillouin scattering fiber sensors," *IEEE SENSORS 2014 Proceedings*, IEEE (2014).
- [63] Lopez-Mercado C.A., Spirin V. V., Nava-Vega A., Mégret Patrice, Fotiadi Andrei, "Láser de Brillouin con cavidad corta de fibra estabilizado pasivamente en la resonancia de bombeo por fenómeno de auto-encadenamiento por inyección óptica," *Revista Mexicana de Física* 60, 53-58 (2014).
- [64] Peled, Y., Motil, A. and Tur, M., "Fast Brillouin optical time domain analysis for dynamic sensing," *Optics Express* 20(8), 8584 (2012).

- [65] E. Preda, A. A. Fotiadi, and P. Mégret, "Numerical approximation for Brillouin fiber ring resonator," *Opt. Express* 20, 5783 (2012).
- [66] Korobko, D. A., Zolotovskii, I. O., Svetukhin, V. V., Zhukov, A. V., Fomin, A. N., Borisova, C. V. and Fotiadi, A. A., "Detuning effects in Brillouin ring microresonator laser," *Optics Express* 28(4), 4962 (2020).
- [67] Debut, A., Randoux, S. and Zemmouri, J., "Experimental and theoretical study of linewidth narrowing in Brillouin fiber ring lasers," *Journal of the Optical Society of America B* 18(4), 556 (2001).
- [68] López-Mercado, C. A., Spirin, V. V., Kablukov, S. I., Zlobina, E. A., Zolotovskiy, I. O., Mégret, P. and Fotiadi, A. A., "Accuracy of single-cut adjustment technique for double resonant Brillouin fiber lasers," *Optical Fiber Technology* 20(3), 194–198 (2014).
- [69] Spirin, V. V., López-Mercado, C. A., Kablukov, S. I., Zlobina, E. A., Zolotovskiy, I. O., Mégret, P., Fotiadi, A. A., "Single cut technique for adjustment of doubly resonant Brillouin laser cavities," *Optics Letters* 38, 2528-2531 (2013).
- [70] Spirin, V. V., Bueno Escobedo, J. L., Korobko, D. A., Mégret, P. and Fotiadi, A. A., "Stabilizing DFB laser injection-locked to an external fiber-optic ring resonator," *Optics Express* 28(1), 478 (2020).
- [71] Spirin, V. V., Bueno Escobedo, J. L., Korobko, D. A., Mégret, P. and Fotiadi, A. A., "Dual-frequency laser comprising a single fiber ring cavity for self-injection locking of DFB laser diode and Brillouin lasing," *Opt. Express* 28(25), 37322 (2020).
- [72] Hansch, T. W. and Couillaud, B., "Laser frequency stabilization by polarization spectroscopy of a reflecting reference cavity," *Optics Communications* 35(3), 441–444 (1980).
- [73] Alnis, J., Matveev, A., Kolachevsky, N., Udem, T. and Hänsch, T. W., "Subhertz linewidth diode lasers by stabilization to vibrationally and thermally compensated ultralow-expansion glass Fabry-Pérot cavities," *Physical Review A* 77(5) (2008).
- [74] D. Derickson, *Fiber Optic Test and Measurement* (Prentice-Hall, 1998).
- [75] Camatel, S and Ferrero, V., "Narrow linewidth cw laser phase noise characterization methods for coherent transmission system applications," *Journal of Lightwave Technology* 26, 3048-3055 (2008).
- [76] Llopis, O., Merrer, P. H., Brahim, H., Saleh, K. and Lacroix, P., "Phase noise measurement of a narrow linewidth CW laser using delay line approaches," *Optics Letters* 36(14), 2713 (2011).
- [77] Li, Y., Fu, Z., Zhu, L., Fang, J., Zhu, H., Zhong, J., Xu, P., Chen, X., Wang, J. and Zhan, M., "Laser frequency noise measurement using an envelope-ratio method based on a delayed self-heterodyne interferometer," *Optics Communications* 435, 244–250 (2019).