Self-injection-locked Brillouin laser with high-Q fiber ring cavity

C. A. Lopez-Mercado[1], D.A. Korobko[2], I.O. Zolotovskii[2], and A.A. Fotiadi [2, 3, 4]
[1]*Autonomous University of Baja California (UABC), Ensenada, B.C., México*
[2]*Ulyanovsk State University, 42 Leo Tolstoy Street, Ulyanovsk, 432970, Russia*
[3]*University of Mons, Electromagnetism and Telecommunication Department, B-7000 Mons, Belgium*
[4]*Ioffe Physical-Technical Institute, RAS, 26 Polytekhnicheskaya Street, St. Petersburg 194021*
Andrei.Fotiadi@umons.ac.be

Abstract: A simple Brillouin fiber laser pumped from a self-injection locked distributed feedback (DFB) laser diode delivers radiation with the Lorentzian linewidth of ~75 Hz and phase noise power density less than –100dBc/Hz (>30 kHz).

Linewidth narrowing and stabilization of semiconductor laser light generation is of great research interest governed by huge demand for compact cost-effective narrow-band laser sources for many potential applications. The simplest approach is based on fiber-optic resonators that could be simply spliced from standard telecom components [1-4]. Recently [4] we have demonstrated a semiconductor DFB laser operating in self-injection locking regime in a combination with simple active optoelectronic feedback. Such a design enables narrowing of the DFB laser linewidth down to ~3 kHz and drastically reduces the laser phase noise. The same idea has been exploited with an all-fiber Brillouin laser [5], where the fiber-optic ring cavity is used simultaneously as external filtered feedback for the DFB laser self-injection locking and as an effective medium for Brillouin Stokes generation. Importantly, 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 [6, 7]. The use of high-Q-factor fiber cavities with a such laser concept could significantly decrease the SBS lasing power threshold, enhance the pump-to-Stokes conversion efficiency and drastically reduce the laser linewidth for a CW Brillouin laser operation.

Here, we report on a new single-mode sub-kilohertz Brillouin fiber laser pumped by a self-injection locked pump DFB laser with active stabilization. Specifically, the new laser design [8] comprises an optical fiber ring cavity with the Q-factor that is almost twice higher than that used with the self-injection locked fiber lasers reported earlier [1-8]. Active optoelectronic feedback based on a simple microcontroller ensures long-term stabilization of the laser operation at pump and Stokes frequencies, simultaneously. The laser stabilization dynamics, linewidth narrowing, and phase noise reduction in the new fiber laser configuration are experimentally explored.

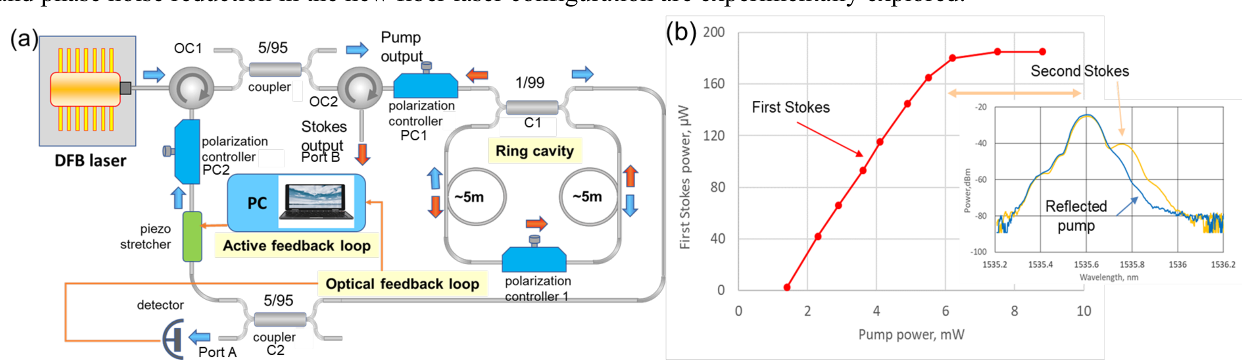

Fig. 1. (a) The experimental laser configuration; (b) Stokes output power as a function of the DFB laser power and output optical spectrum.

The experimental laser setup is shown in Fig. 1. A standard distributed feedback (DFB) laser diode supplied by a -30 dB built-in optical isolator generates radiation with a maximal power of ~10 mW at ~1535.5 nm in linear polarization. The laser radiation passes through the optical circulator (OC1), 95/5 coupler, optical circulator (OC2), polarization controller (PC1), 99/1 coupler (C1), 95/5 coupler (C2), the feedback loop comprising the polarization controller (PC2) and piezo-stretcher (PS), again circulator (OC1) and returns back into the DFB laser cavity thus providing passive optical feedback to the laser operation. The 95/5 coupler redirects a part (5%) of the laser power circulating in the feedback loop (port A) that is used for operation of the electronic feedback circuit and spectrum measurements. The optical fiber ring cavity optically coupled with the feedback loop is spliced from 99/1 coupler (C1) and contains ~11.33 m of a standard telecom fiber (SMF-28e). The circulator and optical isolators isolate the DFB laser from undesirable back reflections from the fiber faces. The high Q-factor optical fiber ring cavity is used simultaneously as a narrow-band optical pass filter attached to the optical feedback loop and as an effective fiber medium to generate Brillouin lasing. Port B of the circulator is used as a Brillouin laser output. The polarization controller (PC1) is used to adjust the polarization state of the light before its introduction to the optical fiber ring cavity providing better coupling of the laser radiation with the resonant ring cavity mode. This process could be monitored through the power detected at port A by a fast photodetector (PD, Thorlabs DET08CFC, 5 GHz, 800 - 1700 nm). The polarization controller (PC2) is used to control the optical feedback strength by adjustment of the light polarization state before its injection to the DFB laser emitting a linear polarization. A piezo fiber stretcher (PFS, Evanescent Optics Inc., Model 915B) attached to the feedback loop is used as an optical phase shitter driven by a low-cost USB Multifunction DAQ (National Instrument NI USB-6009) connected with a PC.

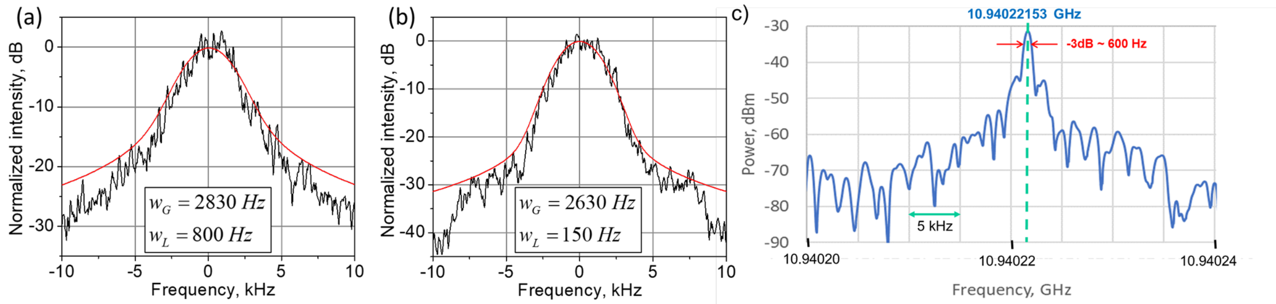

Fig. 2. Delayed self-heterodyne spectra recorded at pump (a, port A) and Stokes (b, port D) laser frequencies and RF spectrum recorded with beating of two channels. The measured spectra (black), their fitting Voigt profiles (red), w_G and w_L are the Gaussian and Lorentzian linewidths.

In contrast to the previous laser configurations [1-6], we have employed the fiber ring cavity built (and then incorporated into the configuration) using just one fiber coupler instead of two couplers used earlier. Such cavity design potentially reduces the optical losses in the ring cavity (twice in comparison with [5]) providing an enhanced Q-factor. Thanks to new Brillouin laser design, the laser performance characteristics has been significantly improved. The Brillouin laser output is increased up to $\sim 180\ \mu W$ from $\sim 100\ \mu W$ reported with the two-coupler ring configuration [5]. Further power scaling is still possible with an external amplifier (it could be a Brillouin amplifier built from the same fiber). The Brillouin lasing threshold power is reduced down to ~1.5 mW comparing with ~2.9 mW observed with even twice longer ring cavity [5]. The Brillouin laser Lorentzian linewidth is reduced down to $\sim 75 Hz$ from $\sim 110 Hz$ measured earlier (see, Fig. 2, a). To the best of our knowledge, it is the narrowest laser linewidth reported with the self-injection locked DFB lasers employing an external fiber cavity [1-6]. These results are in a good agreement with the direct measurements of the radio-frequency (RF) spectrum characterizing the beating between pump and Stokes laser outputs (Fig. 2, b). The spectrum exhibits a pronounced peak with the center at $\sim 10946.3098\ MHz$ and the width of $\sim 600\ Hz$. The peak frequency corresponds to the Brillouin frequency shift in the ring cavity fiber (SMF-28, Corning Inc.) at 1535 nm. The power spectral density of the phase noise is measured to be < –80 dBc/Hz and <–100 dBc/Hz (beyond 30 kHz) for pump and Stokes channels, respectively.

In summary, the laser performance characteristics are quite impressive considering that no significant attempt has been made to stabilize the set-up temperature. They are demanded for many laser applications, including high-resolution spectroscopy, phase coherent optical communications, distributed fiber optics sensing, coherent optical spectrum analyzer, and microwave photonics. The work is supported by Russian Science Foundation (№18-12-00457P) and the Ministry of Science and Higher Education of the Russian Federation (075-15-2021-581).

References

[1] V. V. Spirin et al., "Single-mode Brillouin fiber laser passively stabilized at resonance frequency with self-injection locked pump laser," Laser Physics Letters 9, 377-380 (2012).
[2] C. A. López-Mercado et al. "Locking of the dfb laser through fiber optic resonator on different coupling regimes," Optics Communications 359, 195-199 (2016).
[3] D. A. Korobko et al., "Self-injection-locking linewidth narrowing in a semiconductor laser coupled to an external fiber-optic ring resonator," Optics Communications 405, 253-258 (2017).
[4] V. V. Spirin et al., "Stabilizing DFB laser injection-locked to an external fiber-optic ring resonator," Opt. Express 28, 478-484 (2020).
[5] V. V. Spirin et al., "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).
[6] V. V. Spirin et al., "Single cut technique for adjustment of doubly resonant Brillouin laser cavities," Optics Letters 38, 2528-2531 (2013).
[7] D. Korobko et al., "Detuning effects in Brillouin ring micro-resonator laser," Opt. Express 28, 4962-4972 (2020).
[8] V. V. Spirin et al. "Sub-kilohertz brillouin fiber laser with stabilized self-injection locked dfb pump laser," Optics & Laser Technology 141, 107156 (2021).