Microwave signal generation with a dual-frequency self-injection-locked DFB laser

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ABSTRACT

Low-noise lasers are a powerful tool in precision spectroscopy, displacement measurements, and the development of advanced optical atomic clocks. All applications benefit from lower frequency noise and robust design; however, the generation of microwave signals additionally requires narrowband lasing at two frequencies. Here, we introduce a simple optoelectronic oscillator enabling the generation of a stable ultra-narrow microwave carrier signal with low phase noise based on stimulated Brillouin scattering. A cost-effective sub-kilohertz Brillouin fiber ring laser with stabilized self-injection locked pump DFB (*Distributed Feedback Laser*) laser is used for this purpose. The system is supplied by a low-bandwidth active optoelectronic feedback controlled by a low-cost USB-DAQ card. The full-width of generated microwave signal at -3 dB level is approximately equal to 300 Hz with a peak maximum at ~10.946 GHz. The strongest parasitic harmonics shifted from carrier signal peak by ±50 kHz, ±450 kHz, and ±900 kHz are below the main peak by 45-50 dB. A phase noise below −90 dBc/Hz for a frequency offset above 10 kHz from the carrier after passing the 20 km length test fiber has been achieved.

Keywords: microwave photonics; radio over fiber; self-injection locking; dual-frequency lasing; narrow-band lasing.

1. INTRODUCTION

Emerging of the Internet of Things (IoT) and recent progress in 5G communications are linked to development of wireless communication systems with incorporated multiple services and smart devices ensuring a high-speed data transmission. The integration of wireless and optical networks is a feasible and low-cost solution able to satisfy the growing demand for data traffic, new services, and to provide compatibility with multiple wireless communication standards opening prospects for Radio over Fiber (RoF) technologies [1, 2]. Microwave signal generation using narrow-band laser radiation and its further processing in optical domain is a key technique ensuring high quality and low cost for a RF carrier transmission in RoF systems. Several techniques have been proposed to generate microwave signals in the GHz spectrum range. Beating of two narrow-band lasers operating at different wavelengths, phase and intensity modulation of narrowband optical signals, mode-locked laser operation and specific effects of non-linear optics are among them [3-15].

Stimulated Brillouin Scattering (SBS) in optical fibers is a non-linear phenomenon that could be employed for RF signal generation [16, 17]. SBS in fiber optics is characterized by a low threshold and narrow bandwidth that are quite promising for realization of narrowband RF filters and high-frequency optoelectronic generators possessing ultra-low phase noise [18-21]. However, to get GHz frequency generation with SBS for application in RoF systems a single-frequency narrow-band low-noise laser pumping is important [22-32].

Recently, we have proposed a laser concept [33-43], where the self-injection locking mechanism [44-48] in combination with a simple active optoelectronic feedback provides linewidth narrowing of a commercial DFB laser down to ~220 Hz decreasing the laser phase noise as well [43]. A similar design has been used to build all-fiber Brillouin lasers [49, 50], where an external fiber optic ring resonator (FORR) is used simultaneously as a narrow-band filter providing the DFB laser linewidth narrowing and a medium for generation of the Brillouin Stokes wave. The use of high Q-factor FORR in such a configuration allows to decrease the SBS power threshold ensuring a stable generation of a single Stokes frequency with a low Stokes radiation noise. The beating between Stokes and pump radiations results in RF frequency generation at ~11 GHz, making the laser promising for generation of microwave signals in multiple applications.

In this work, we demonstrate, to the best of our knowledge for the first time, the GHz signal generation provided by a low-cost single-frequency sub-kHz Brillouin fiber laser stabilized through the self-injection locking of the pump DFB laser. The self-locking mechanism ensures a drastic linewidth narrowing of the DFB laser important for generation of the Stokes wave with a low power threshold. A microcontroller based on active optoelectronic feedback stabilizes the laser operation in self-injection locking regime preventing mode-hopping. The stabilized laser configuration generates a low-cost microwave signal with a very low phase noise important for RoF applications.

2. EXPERIMENTAL SETUP

The experimental configuration of the Brillouin laser system shown in Fig.1 has been used to generate a harmonic RF signal at 11 GHz of a high spectral purity. The Brillouin fiber laser is pumped by a distributed feedback (DFB) laser diode exhibiting injection-locking through an external FORR (fiber optic ring resonator). The DFB laser supplied by a built in -30dB isolator operates at ~1535 nm with the laser linewidth of ~3.2 MHz and maximal optical power of ~5 mW. The laser radiation passes through the two optical circulators, OC1 and OC2, a variable coupler CV1 and FORR. The FORR of 21.17-m length is built from two 99/1 couplers (C3 and C4) and a standard telecommunications SMF-28 fiber. In general, the FORR is similar to the Fabry-Perot linear cavity with 99% reflectivity of both mirrors, where port C (Fig.1) is equivalent to the reflected port of the lineal cavity. This FORR configuration is used as a frequency selective element included into an optical feedback loop making the DFB laser operate in self-injection regime with a drastic linewidth narrowing. The same FORR is used as a medium for generation of the Stokes radiation through the SBS. The optical isolators and circulators block reflection from detectors and fiber ends. When the frequency of the DFB laser is resonant to the FORR, the maximum coupling of the input radiation and the cavity is achieved leading to an increase of the DFB laser power circulating inside the resonator. In this case, the DFB laser power passes freely through the FORR and provides the maximum level of the optical feedback leading to self-injection locking of the DFB laser. At the same time, the reflected power at port C decreases to its minimum value. In the self-injection locking regime, the linewidth of the DFB laser is drastically reduced and the laser operates at the FORR resonant frequency.

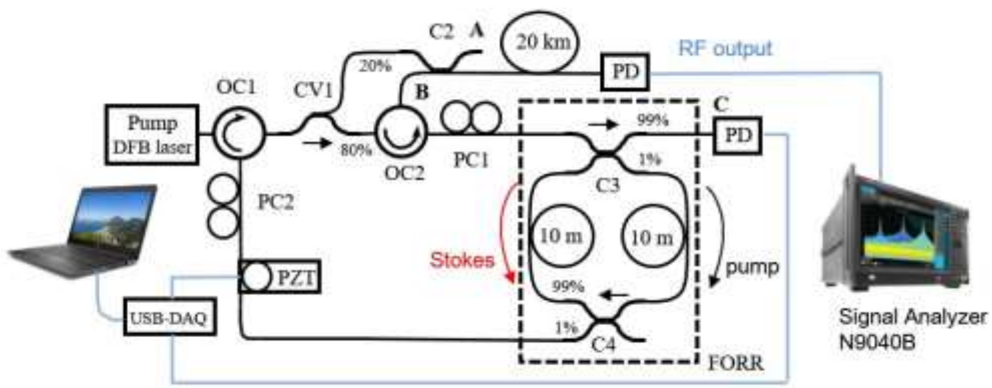

Fig.1. Experimental setup: USB-DAQ – microcontroller, PD –photodetector, OC- optical circulator, PC – polarization controller, CV1 – variable coupler, C – coupler, PZT-fiber piezo stretcher, FORR –fiber optic ring resonator.

To make the laser cavity resonant to both pump and Stokes radiation (a cavity with double resonance), single-cutting technique has been applied to ~21.5 m FORR length [42]. With this technique, cutting the fiber once allows us to adjust the maximum of the Brillouin gain spectrum to the peak of the FORR resonance mode and thus reduce the Brillouin threshold. The final FORR length corresponding to the minimum of the Brillouin threshold is 21.17 m. In the experiment, when the pump input power exceeds 2 mW, the pumping power circulating inside the ring clockwise (CW enables generation of the first Brillouin Stokes in the counterclockwise (CCW) sense. Commonly, self-injection locking occurs when the free DFB laser frequency differs from the resonance peak of the FORR by less than a few tenths of MHz [37]. Beyond this range, a small variation in environmental parameters destroys self-injection locking causing mode-hopping. Deviation of the laser frequency from the FORR resonance could be monitored through recording of the laser power reflected or transmitted through the FORR.

The task addressed to the additional electronic feedback is to keep the laser frequency in a proximity to the FORR resonance, i.e. within the range suitable for laser operation in self-injection locking regime. In the experiment, a simple active feedback based on a simple and low-cost data acquisition card (USB-DAQ) is used. The USB-DAQ connected to a PC provides a precise adjustment of the optical feedback loop length keeping the resonance between the laser frequency and FORR optical mode. For this operation, the USB-DAQ controls the voltage applied to the piezo-activator attached to the optical feedback loop and the FORR reflected power detected by a fast photodiode is used as an error signal. The control algorithm is intended to keep the value of the reflected power as low as possible, thus excluding even slow fluctuations. This technique enables a stable DFB laser operation in the self-injection locking regime at the frequency centered to the FORR transmission peak that results in mode-hopping free generation of a narrow-band Stokes radiation.

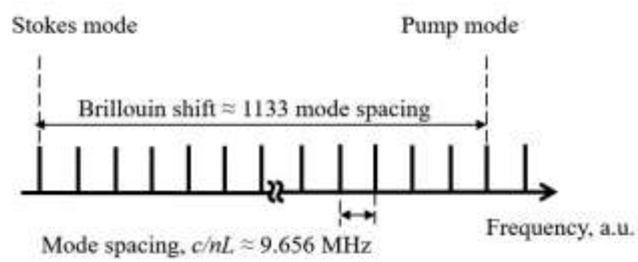

Fig. 2. FORR optical modes.

The Brillouin laser based on SMF-28 fiber generates the Stokes radiation shifted by ~11 GHz from the pump frequency [16]. With the ring length of ~21.17 m and the refractive index n = 1.4679 (SMF-28 fiber [51]) the FORR free spectral range is ~9.656 MHz. So, we can conclude that in our experiment both pump and Stokes laser frequencies are the FORR optical modes spaced by 1133 FSRs (see Fig. 2). The combining of two laser outputs by the optical coupler C2 (Fig. 1) allows to generate RF signal though the beating of the pump and Stokes laser radiations

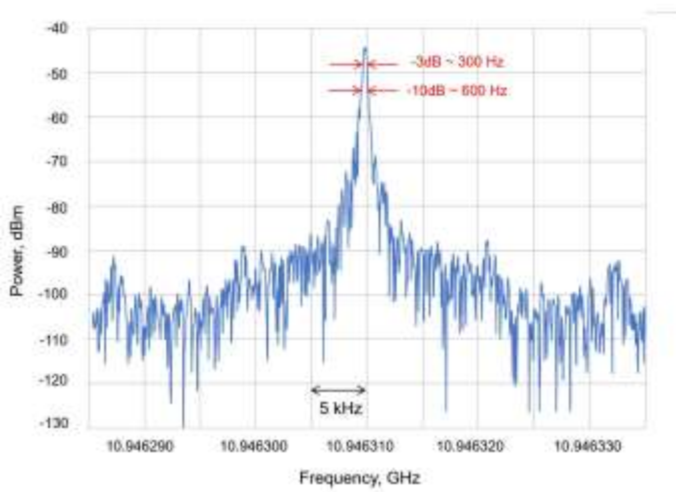

Fig. 3. The RF signal spectrum at ~10.946 GHz.

3. EXPERIMENTAL RESULTS AND DISCUSSION

Figure 3 shows the RF spectrum recorded with the beat of the pump and Stokes radiation generated by the laser at the ring fiber temperature of ~19˚C. The 50-GHz spectrum analyzer (Keysight N9040B) supplied by a 12 GHz photodetector is used for this purpose. The maximum beat RF spectrum peak is at ~10.946 GHz and its full width is ~300 Hz (FWHM). Since the difference between the pump and Stokes frequencies is significant, we can ignore the correlation effects between the two laser outputs. In this case, the reported RF spectrum confirms that the optical linewidths of both pump and Stokes waves is narrower than ~200 Hz. It is worth noting that the resolution limit of our measurements is ~100 Hz.

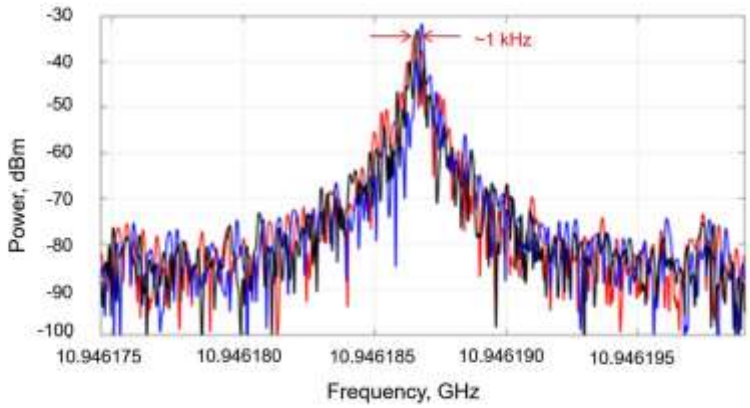

Fig. 4. RF frequency drift for 10 minutes.

Figure 4 shows the drift of the carrier frequency due to environmental temperature fluctuations measured during~10 minutes. Although no special procedure is applied to stabilize the FORR, the frequency drift is found to be less than 1 kHz that is good enough for many microwave applications [52, 53]. With the RF spectrum peak frequency of ~11GHz the frequency drift over ~1.1 kHz corresponds to the RF generator stability <0.1 ppm [54]. The RF frequency drift can be further decreased using the system protection from the temperature fluctuations and environment noise.

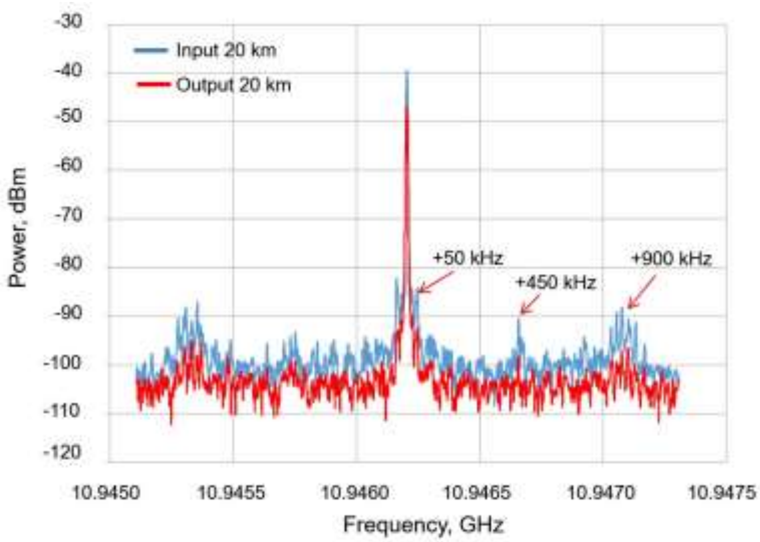

Fig. 5. Spectrum of the carrier signal and its harmonic components at the 20 km optical fiber input and output.

We have estimated the changes of the RF spectrum parameters after propagation of both optical signal generated by the laser through the 20 km optical fiber length. Figure 5 shows the RF spectrum phase noise measured before and after such transmission. One can see that the RF spectrum along with the main peak corresponding to the Brillouin frequency shift in the laser comprises its harmonic components observed at ±50 kHz, ±450 kHz, ±900 kHz. The amplitudes of these components are by 45-50 dB lower than the main peak. The harmonic components of such low amplitude could not deteriorate high spectral purity of the RF signal. Their typical acceptable values reported earlier are between -30 and -60 dBc depending on the operating frequency range [54]. We have found that the peak frequency of the RF signal does not change after transmission, while the amplitude of the harmonic components decreases by 6-7 dB due to the optical losses in the 20 km length of the optical fiber and connectors. It is important to note that at the fiber output the peak of harmonic components falls below the noise floor of the spectrum, and so can be considered as negligible.

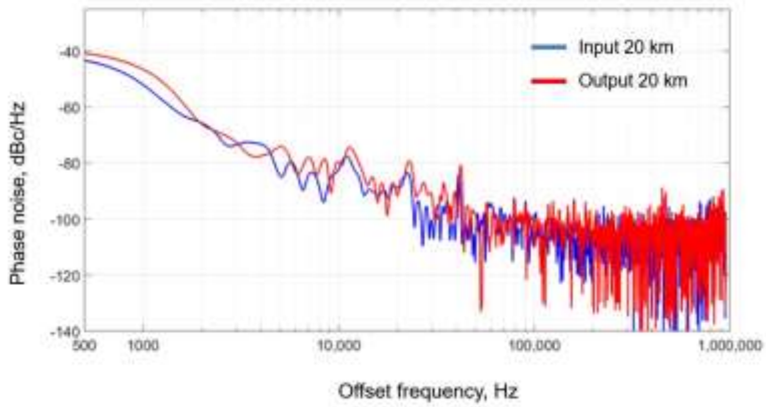

Fig. 6. Phase noise at the input and output of the 20 km optical fiber.

Figure 6 shows the phase noise of the RF signal at 11 GHz at the input and output of the 20 km optical fiber measured for the offset frequencies <1 MHz. One can see that after the RF signal passage through the fiber its phase noise increases insignificantly (by 1-2 dB only). For the offset frequencies >10 kHz it is well below −90 dBc/Hz that is good enough for many microwave applications [3-6, 54]. In the experiment, the phase noise of the RF signal significantly increases in the situation when the change of the environment temperature causes the pump laser frequency drift too far from the laser frequency corresponding to the optimal double cavity resonance condition thus disturbing effective generation of the Stokes wave. So, thermal control of the laser system allows to reduce the phase noise. Another way to reduce the phase noise is the use of the FORR with higher Q-factor. The reported RF signal characteristics confirm the capacity the proposed RF generator for multiple RoF applications.

3. CONCLUSION

In conclusion, we have proposed and tested a new optoelectronic tool for generation of an ultra-narrow microwave carrier signal at 11 GHz with low phase noise. This effective and low-cost solution is based on a sub-kHz ring fiber optic Brillouin laser supplied by an active stabilization with USB-DAQ control of self-injection locking DFB laser operation. Above the threshold of 2 mW, the FORR laser configuration emits the pump and Stokes radiation, simultaneously. Their coupling at the photodetector enables generations of a RF beating signal possessing high spectral purity and low phase noise. The FWHM of the RF spectral peak is ~300 Hz at the frequency of ~10.946 GHz. The RF spectrum comprises parasitic harmonics shifted by ± 50 kHz, ± 450 kHz and ± 900 kHz from the main RF peak. However, their level is by 45-50 dB lower than the main peak amplitude. The RF generator phase noise is less than -90 dBc/Hz. We have also demonstrated transmission of the laser output signals over 20 km through the optical fiber without degradation of the RF signal performance. The obtained results make the proposed low-cost solution promising for application in radio over fiber systems. Other potential applications of the reported system include high-resolution spectroscopy, phase coherent optical communications, microwave photonics, coherent optical spectrum analyzer, distributed fiber optics sensing, in particular, phase-OTDR acoustic sensing [55-96].

ACKNOWLEDGEMENTS

This work on the system design and characterization was supported by the CONACYT, Mexico (projects INFR-2016-01 No. 269927) and the Ministry of Higher Education and Science of the Russian Federation (Megagrant Program, project # 2020-220-08-1369). The work on the dual-frequency laser metrology and minimization of the laser frequency drift was supported by the Russian Science Foundation (project 18-12-00457).

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