# Highly Stable Low-Noise Brillouin Fiber Laser With Ultranarrow Spectral Linewidth

Jihong Geng, Sean Staines, Zuolan Wang, Jie Zong, Mike Blake, and Shibin Jiang

***Abstract*—We demonstrate an all-fiber high-power single-frequency Brillouin fiber ring laser with maximum power of 100 mW at 1.55 $\mu$m, which is actively stabilized by using the Pound–Drever–Hall frequency-locking scheme. Significant reduction (~20 dB) of both relative intensity noise and frequency noise was observed in the Brillouin Stokes radiation as compared with those noises of its pump source, a narrow-linewidth Er-doped fiber laser. Ultranarrow spectral linewidth of the Brillouin fiber lasers was investigated by both delayed self-heterodyne technique and heterodyne beat technique between two independent Brillouin fiber lasers.**

***Index Terms*—Brillouin scattering, fiber laser, frequency noise, intensity noise, laser linewidth, stabilization.**

## I. INTRODUCTION

COHERENT laser sources with both low intensity noise and low frequency noise are an essential requirement for a variety of applications, such as coherent optical communication, coherent ladar detection, interferometric sensing, and microwave photonics. Diode-pumped single-frequency solid-state lasers (including fiber lasers) are the best-known low-noise coherent laser sources with a spectral linewidth ranging from hundreds of kilohertz to as narrow as a few kilohertz [1]–[4]. These lasers have also the potential to produce near-quantum-limited intensity noise by combining the use of an amplitude squeezed pump diode and an electronic feedback loop.

Single-frequency Brillouin fiber ring lasers are another type of highly coherent light source that has been attracted significant interest for decades due to their linewidth narrowing effect [5]–[7]. Experiments have demonstrated that free-running spectral linewidth of single-frequency Brillouin fiber ring lasers could potentially be only a few hertz, which can be several orders of magnitude narrower than that of their single-frequency pump beams. To obtain stable operation in Brillouin fiber lasers practically, active stabilization by means of a fast feedback loop is required because Brillouin laser operation is extremely sensitive to resonance detuning between the pump laser frequency and the Brillouin cavity mode. However, the use of a stabilizing feedback loop may introduce some modulations on the Brillouin cavity, resulting in a degraded linewidth performance; even worse than that of its pump laser [8].

Recently, Stepien *et al.* have extensively studied relative intensity noise (RIN) of Brillouin fiber lasers theoretically [9]. They derived intensity noise transfer functions and further predicted that there could be an intensity noise reduction in Brillouin fiber lasers. However, they were not able to confirm the prediction experimentally because the laser was not sufficiently stabilized to permit such an RIN measurement. In this letter, we present an all-fiber actively stabilized Brillouin fiber laser with high output power and low noise. RIN, frequency noise, and heterodyne linewidth of the low-noise Brillouin fiber laser have been investigated.

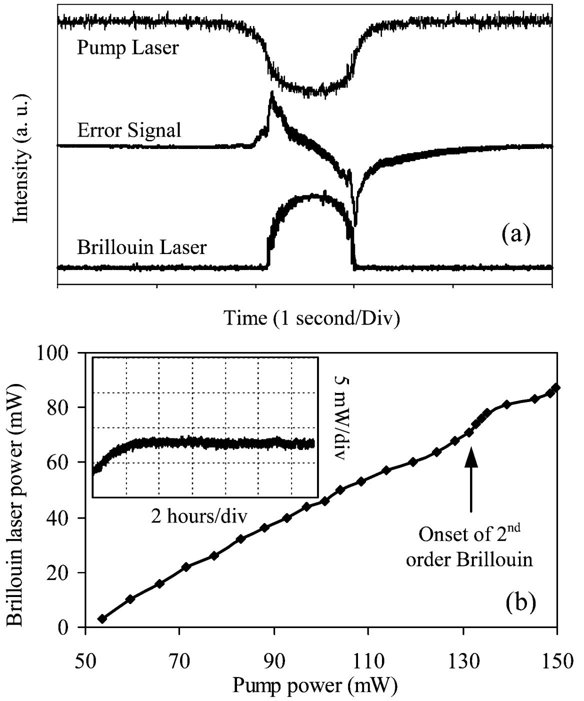

Fig. 1. (a) Error signal with respect to the pump and Brillouin lasers in the Pound–Drever–Hall frequency-locking scheme. (b) Brillouin laser output power as functions of pump laser power and time. Inset: Long-term monitor of the laser.

## II. BRILLOUIN FIBER LASER

The Brillouin fiber laser is pumped by a high-power piezo-electrically tuned Er-doped fiber laser at 1550 nm (Scorpion, NP Photonics), as described in details elsewhere [10]. The Pound–Drever–Hall frequency-locking technique [11] was used to actively stabilize continuous-wave operation of the single-frequency Brillouin fiber laser by rapidly tuning the pump laser frequency to keep it resonant with the Brillouin ring cavity. Fig. 1(a) shows the error signal with respect to both the pump and Brillouin lasers in the frequency-locking scheme. The error signal was generated with a lock-in amplifier by monitoring the transmitted pump power through the ring cavity. When the pump laser frequency is resonant with the Brillouin laser cavity, as shown in Fig. 1(a), maximum coupling of the pump beam into the Brillouin cavity is obtained, resulting

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The authors are with NP Photonics, Inc., Tucson, AZ 85747 USA (e-mail: geng@npphotonics.com).

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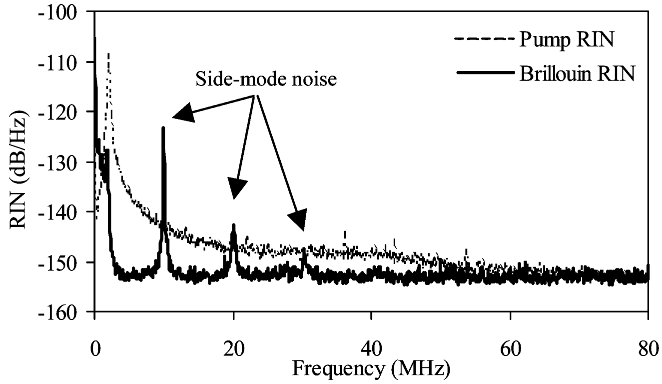

Fig. 2. RIN spectra of both the Brillouin laser (thick line) and its pump laser (thin line).

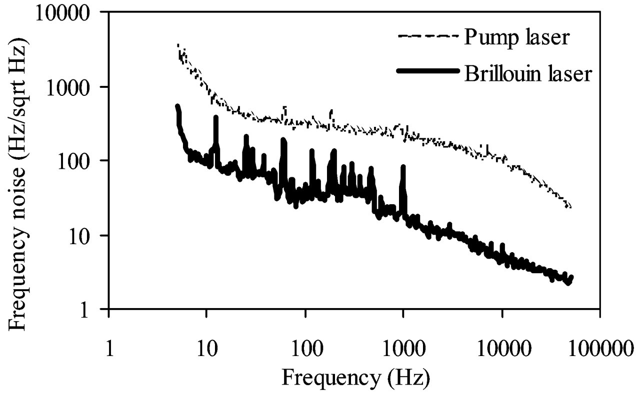

Fig. 3. Frequency noise spectra of both the Brillouin laser (thick line) and its pump laser (thin line).

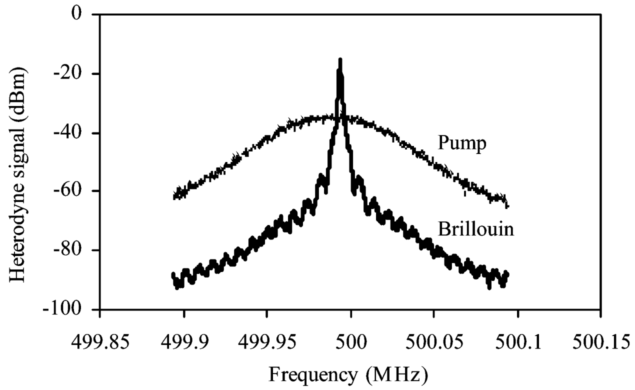

Fig. 4. Delayed self-heterodyne spectra of the lasers using 25-km fiber delay.

in the generation of the stimulated Brillouin laser radiation. The pump laser frequency can be locked to the Brillouin cavity by feeding the error signal back to the pump laser through a piezo actuator. Thus, the temperature-controlled and vibration-damped Brillouin cavity keeps stationary stable without any active disturbance in the Brillouin laser. Stable operation of the Brillouin laser can be maintained over 14 h [see the inset of Fig. 1(b)]. Fig. 1(b) also shows the Brillouin laser output power that was measured after a circulator. If a 0.45-dB loss of the circulator is taken into account, the maximum output power in front of the circulator is about 90 mW with 95% slope efficiency. When the pump power reaches 130 mW, the second-order stimulated Brillouin radiation starts to emit in the cavity.

## III. LASER PERFORMANCE

Intensity noise and frequency noise of the Brillouin laser have been fully characterized and they have been compared with the noises of its pump laser. Fig. 2 shows RIN spectra of both the Brillouin laser and its pump that were measured with 0.5-mA photocurrent. It can be seen that the RIN spectra of the pump laser is dominated by the laser relaxation oscillation at 2 MHz [2]. This noise peak has been transferred to the Brillouin laser after reducing by 20 dB. This is, to our knowledge, the first time to confirm intensity noise reduction in a Brillouin fiber ring laser experimentally. The Brillouin laser has a major intensity noise peak at 10 MHz, which comes from sidemode noise. Other than these peaks, the RIN of the Brillouin laser goes down to $-152$ dB/Hz, corresponding to the shot noise limit at the 0.5-mA photocurrent.

Frequency noise of the lasers was measured by using an unbalanced Michelson fiber interferometer with 100-m unbalanced fiber length. Fig. 3 shows the frequency noise spectra of both the Brillouin laser and its pump. More than 10-dB reduction in frequency noise is observed in the Brillouin laser as compared with its pump laser. Multiple frequency noise peaks appeared in the Brillouin laser spectra are due to environmental vibration and electrical noises (60 Hz and its harmonics) from power supply.

Delayed self-heterodyne technique was used to investigate the ultranarrow linewidth of the Brillouin fiber laser. Fig. 4 shows delayed self-heterodyne spectra of both the Brillouin laser and its pump laser, which were measured with 25-km fiber delay. We take the 20-dB down linewidth from the self-heterodyne spectrum that was 4 and 150 kHz for the Brillouin and pump laser, respectively. For the pump laser, the full-width at half-maximum (FWHM) linewidth can be derived to be 7.5 kHz if the lineshape is Lorentzian [12]. It should be noted that lineshape-fitting analysis indicates a significant deviation of the self-heterodyne spectra from a Lorentzian. This deviation is attributed to the frequency-dependent frequency noise of the lasers [2], [4]. For the Brillouin laser, it is clear that the delay length is too short to obtain incoherent mixing (incoherent mixing is required in this technique) as evidenced by the oscillatory shape of the signal. Practically, achieving incoherent self-mixing of the Brillouin fiber laser is difficult since the coherence length is estimated to be at least hundreds kilometers.

Heterodyne beat technique [12] was also used to investigate linewidth of the Brillouin fiber lasers. Two different configurations were used to generate heterodyne beat spectra between two similar Brillouin fiber lasers. The first configuration was to use a single pump laser to generate two Brillouin laser beams in two similar independent ring cavities. Heterodyne beat spectrum between the two independent Brillouin lasers was shown in Fig. 5(a). The second configuration was to use two independent pump lasers to generate two Brillouin laser beams in a single fiber ring cavity. The wavelength of the two pump lasers was tuned to be very close (<0.01 nm) so that the beat frequency was within the bandwidth of the detection system. Fig. 5(b) shows the heterodyne beat spectrum in the second configuration. Both

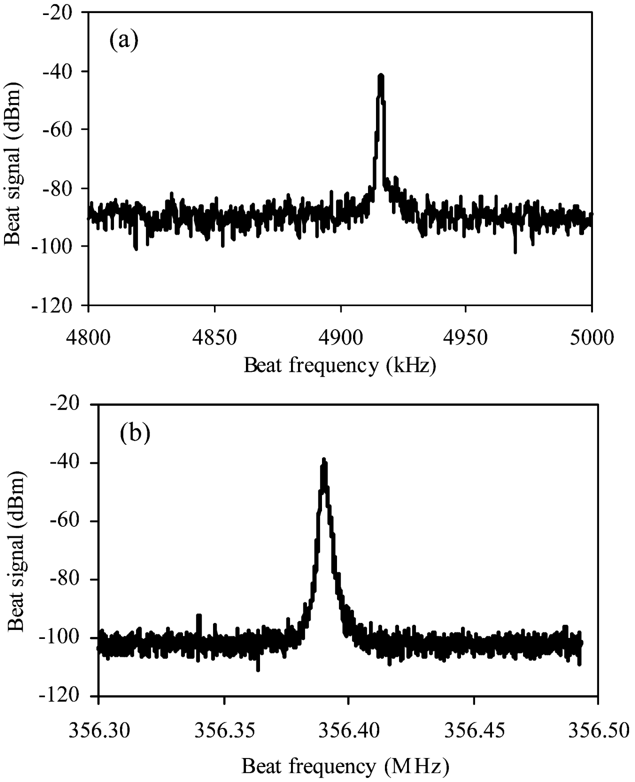

Fig. 5. Heterodyne spectra of the two Brillouin fiber lasers. (a) Beat spectrum between two Brillouin lasers in two independent ring cavities sharing a single pump laser; (b) beat spectrum between two Brillouin laser beams generated in a single ring cavity pumped with two independent pump lasers.

spectra in Fig. 5 have 200-kHz frequency span in half-second timescale. It is interesting that the two heterodyne beat spectra show slightly different linewidth; although both are very close to the bandwidth resolution (1 kHz) of the electrical spectrum analyzer used in the experiment. The spectral linewidth in the first configuration is slightly narrower than that in the second one, indicating contribution of pump laser coherency. We measured the 20-dB down linewidth of the beat signals in Fig. 5 that is 2.4 and 2.8 kHz, respectively. Accurate FWHM linewidth measurement needs an electrical spectrum analyzer with higher bandwidth resolution.

We can estimate the linewidth of our Brillouin fiber lasers based on previous theoretical analysis performed by Debut [7]. A simple analytical relation connecting Brillouin laser linewidth $\Delta\nu_{\mathrm{stokes}}$ and pump laser linewidth $\Delta\nu_{\mathrm{pump}}$ is given by

$$\Delta\nu_{\mathrm{stokes}} = \frac{\Delta\nu_{\mathrm{pump}}}{\left(1 + \frac{\gamma_A}{\Gamma_C}\right)^2} \tag{1}$$

where $\gamma_A = \pi\Delta\nu_B$ and $\Gamma_C = -c\ln R/nL$ are the damping rate of the acoustic wave and the cavity loss rate. Our Brillouin fiber laser has a coupling ratio $R = 0.5$ and cavity length $L = 20$ m with Brillouin gain bandwidth $\Delta\nu_B \sim 20$ MHz. We derive that $\Delta\nu_{\mathrm{stokes}} \approx \Delta\nu_{\mathrm{pump}}/100$. Thus, the Brillouin laser linewidth is about 75 Hz since the pump laser linewidth is 7.5 kHz.

## IV. CONCLUSION

We have demonstrated a highly stable Brillouin fiber ring laser at 1.55 $\mu$m with high output power and low noise by use of the Pound–Drever–Hall frequency-locking scheme. Both intensity noise and frequency noise of the single-frequency Brillouin fiber laser were characterized, which exhibit significant noise reduction, as compared with those noises of its pump source. The ultranarrow linewidth has been investigated by both delayed self-heterodyne and heterodyne beat techniques. Accurate linewidth measurement was limited by resolution of the electrical spectrum analyzer.

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