Pump-to-Stokes transfer of relative intensity noise in Brillouin fiber ring lasers

Jihong Geng and Shibin Jiang

NP Photonics, Inc., 9030 South Rita Road, Tucson, Arizona 85747, USA

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We have experimentally investigated pump-to-Stokes intensity noise transfer in both the frequency domain and the time domain in all-fiber single-frequency Brillouin ring lasers. In the high-frequency region (>1 MHz), the pump-to-Stokes noise transfer function can be much smaller than unity, indicating that the Brillouin fiber lasers act as an efficient low-pass filter. The maximum noise reduction of 40–60 dB was observed at antiresonant frequencies that are multiples of half the cavity free spectral range. This is the first experimental demonstration, to the authors' knowledge, of intensity noise reduction in Brillouin fiber lasers.

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Single-frequency Brillouin fiber lasers are a special type of coherent laser source that differs significantly from conventional single-frequency solid-state or fiber lasers. Experiments have demonstrated that spectral linewidth of a free-running single-frequency Brillouin fiber ring laser could be only a few hertz,[1] which can be several orders of magnitude narrower than that of their pump lasers.[2–4] As a comparison, the pump lasers of Brillouin fiber lasers usually are single-frequency diode-pumped solid-state lasers (including fiber lasers), which have a linewidth as narrow as a few kilohertz.[5,6] The most important difference between the two types of laser is that the laser gain in Brillouin fiber lasers results from nonlinear stimulated Brillouin scattering in fiber, instead of population inversion of active ions in conventional solid-state or fiber lasers. Theoretically, Brillouin fiber lasers have been successfully characterized by a three-wave interaction model of stimulated Brillouin scattering.[3,4] These characterizations include theoretical prediction of the linewidth narrowing effect in Brillouin fiber lasers. It has been shown that both acoustic damping and cavity feedback are responsible for phase noise reduction of the pump laser, thereby yielding a much narrower spectral linewidth in single-frequency Brillouin fiber lasers.

In addition to phase noise or spectral linewidth, intensity noise is another very important figure-of-merit of a single-frequency laser. Highly coherent laser sources with both low phase noise and low intensity noise are expected to be very useful for a variety of applications. In contrast with those experimental demonstrations of the linewidth narrowing effect in single-frequency Brillouin fiber lasers, there have been very few reports of the intensity noise properties of a Brillouin fiber laser so far. Recently, Zemmouri's group reported a comprehensive investigation of the intensity noise properties of Brillouin fiber lasers.[7] Using the three-wave interaction model, they numerically calculated intensity noise transfer functions of Brillouin fiber lasers under various conditions. It is of special interest that their calculations predicted that in some cases the intensity noise of Brillouin fiber lasers could be lower than that of the Brillouin lasers' pump lasers, especially at some frequency regions for a high-finesse cavity. However, this prediction has never been confirmed experimentally, partly due to the lack of a stable Brillouin fiber laser source. In the experiment, they were not even able to measure the relative intensity noise (RIN) spectrum of their bulky Brillouin fiber laser because the laser was not stable enough to perform such a measurement. Although the pump-to-Stokes RIN transfer functions have been determined experimentally, the results did not show any significant noise reduction in the Brillouin fiber lasers. Instead, a degraded intensity noise was reported as compared with their pump laser.

More recently, we reported an actively stabilized all-fiber single-frequency Brillouin laser with extreme narrow linewidth.[8] The high stability of our Brillouin fiber laser allowed us, for what is believed to be the first time, to measure the RIN spectrum of a Brillouin fiber laser, which showed a significantly reduced RIN in most frequency regions as compared with its pump source. In this Letter, we study the pump-to-Stokes RIN transfer in our actively stabilized Brillouin fiber lasers with different cavity parameters and present what is to our knowledge the first experimental demonstration of RIN reduction in all-fiber Brillouin lasers.

The Brillouin fiber laser is pumped by a high-power piezoelectrically tuned Er-doped fiber laser at 1550 nm, as described in detail elsewhere.[8] We slightly modified the experimental setup. An intensity modulator (EO) was placed right after the pump laser, as shown in Fig. 1. The modulated pump beam

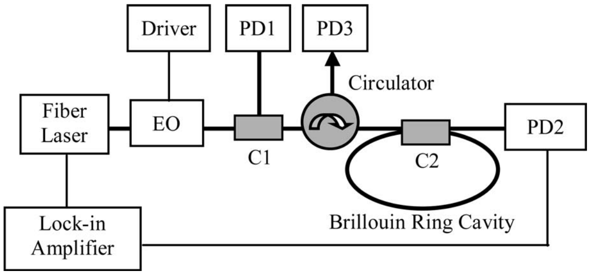

Fig. 1. Experimental setup.

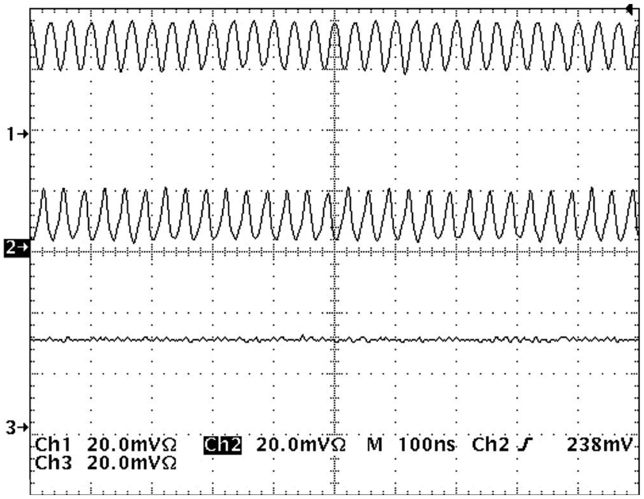

Fig. 2. Typical oscilloscope traces of the pump beam (upper), transmitted pump beam (middle), and Brillouin beam (lower) when a 30 MHz sine wave modulation was applied to the pump laser.

was monitored by a photodiode (PD1) through a tap coupler (C1). The Brillouin fiber laser beam, emitted from a ring cavity formed by a directional polarization-maintaining fiber coupler (C2) and a long piece of standard polarization-maintaining fiber, was efficiently extracted through a fiber circulator. The use of polarization-maintaining fiber in the ring cavity enables us to eliminate the effect of fluctuations of the cavity reinjection rate[7] (through polarization-dependent loss of the fiber coupler) on the measurement of the pump-to-Stokes RIN transfer function. As described in Ref. 8, the Pound–Drever–Hall (PDH) frequency-locking technique was used to actively stabilize continuous-wave operation of the single-frequency Brillouin fiber laser. A tiny amount of frequency modulation was applied to the pump laser at a relatively low frequency (~1 kHz) for frequency dithering in the PDH scheme. The error signal in the PDH feedback loop was generated with a lock-in amplifier by monitoring the transmitted pump power with a photodiode (PD2). The frequency locking is realized by feeding the error signal back to the pump laser to keep the pump laser frequency in resonance with the Brillouin ring cavity. The bandwidth of the feedback loop was designed to be limited to a few kilohertz. But the frequency applied to the EO for pump intensity modulation was varied from 100 kHz to 80 MHz, which is far beyond the PDH loop bandwidth, so that the intensity modulation of the pump laser has almost no impact on the feedback loop. When the PDH feedback loop is closed, stable operation of the Brillouin laser can be maintained over hours even when significant intensity modulation is applied to the pump laser. Figure 2 shows typical oscilloscope traces of the pump beam (from PD1), the transmitted pump beam (PD2), and the Brillouin beam (PD3) when the pump laser intensity was sinusoidly modulated at 30 MHz. It is very clear to see in Fig. 2 that in the time domain no response to the pump modulation can be seen in the Brillouin fiber laser.

When a sine wave voltage at a specific frequency ranging from 100 kHz to 80 MHz was applied to the pump beam through the EO modulator, we used an electrical spectral analyzer to measure the RIN spectra of both the modulated pump beam (from PD1) and the Brillouin beam (PD3). Then, pump-to-Stokes RIN transfer functions can be determined by measuring the ratio of the RIN peak of the Brillouin laser to the RIN peak of the modulated pump laser as a function of modulation frequency. In units of decibels (dB), it is simply the RIN difference between the Brillouin fiber laser and its pump laser. Figures 3 and 4 show the pump-to-Stokes RIN transfer functions measured in two Brillouin fiber lasers with different cavity finesse and different pump rates. The high-finesse Brillouin cavity was formed by a high-reflectivity directional fiber coupler ($R=95\%$), while the low-finesse cavity has a low-reflectivity coupler ($R=50\%$). The modulation frequency was normalized to the free spectral range (FSR, ~10 MHz) of the Brillouin ring cavities in both cases. The pump rate μ is defined as the ratio of pump laser power to the threshold pump power.

It can be seen from the data in Figs. 3 and 4 that our experimental results are qualitatively in agreement with the previous theoretical predictions. As predicted in Ref. 7, the pump-to-Stokes RIN transfer functions exhibit resonance at frequencies that are multiples of the cavity FSR. A high-finesse-cavity Brillouin fiber laser has a lower intensity noise than a low-finesse-cavity laser. Also, the transfer functions have greater values at low frequencies than that at high frequencies regardless of the cavity finesse.

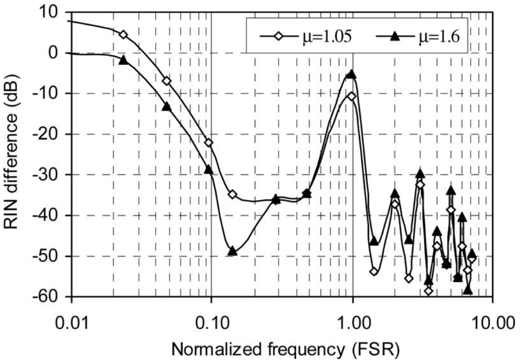

Fig. 3. Pump-to-Stokes RIN transfer for high-finesse Brillouin fiber laser ($R=95\%$) at different pump rates.

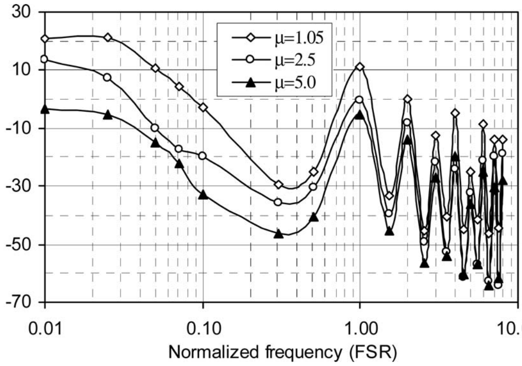

Fig. 4. Pump-to-Stokes RIN transfer for low-finesse Brillouin fiber laser ($R=50\%$) at different pump rates.

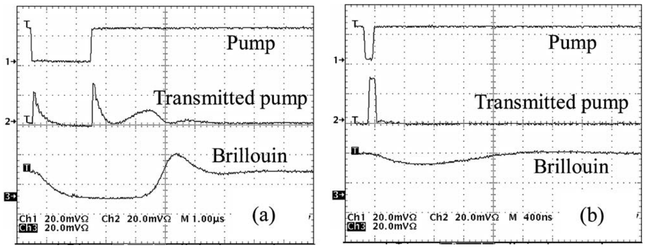

Fig. 5. Transient response of the single-frequency Brillouin fiber laser to a short period of pump off (a) 2 μs and (b) 100 ns.

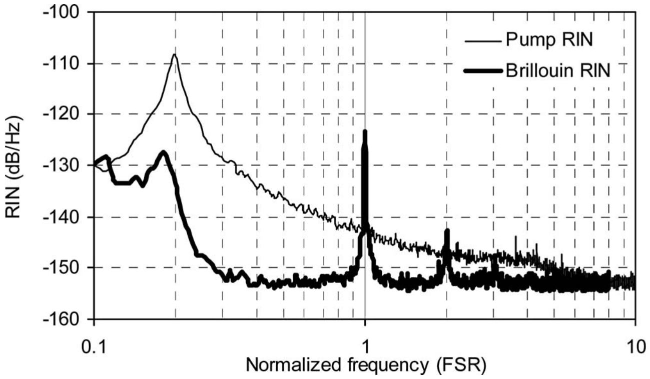

Fig. 6. RIN spectra of both the Brillouin fiber laser ($R = 50\%$) and its pump laser without EO modulation.

It is noted that, however, our experimental results quantitatively reveal some different features in Brillouin fiber lasers from the previous predictions. For the Brillouin fiber lasers with either a high- or a low-finesse cavity, the measured pump-to-Stokes RIN transfer functions at nonresonant frequencies (>1 FSR) are several orders of magnitude smaller than unity at any pump level. At the antiresonant frequencies that are multiples of half the cavity FSR, the maximum noise reduction of 40–60 dB was observed. Even at resonant frequencies, which are multiples of the cavity FSR, transfer functions were still much lower than unity. This indicates that Brillouin fiber lasers act as an efficient low-pass filter that can significantly reject all high-frequency components of pump laser intensity noise.

Noise rejection at high frequencies in the Brillouin fiber lasers is also demonstrated in the time domain. Figure 5 shows the transient response of a single-frequency Brillouin fiber laser to a short period of pump off. When the pump-off duration is longer than 1–2 μs, the pump beam intensity circulating inside the Brillouin cavity was reduced to less than pump threshold by pump depletion and cavity coupling loss [see Fig. 5(a)]. As a result, the Brillouin laser experiences a complete decay and re-buildup processes of the Stokes beam inside the ring cavity. When the pump-off duration is short enough [e.g., 100 ns in Fig. 5(b)], the pump intensity stored inside the Brillouin cavity still keeps above pump threshold and the Brillouin laser oscillation sustains CW operation. The fast intensity fluctuation (short pump-off process) of the pump laser has been smoothed by intracavity beam accumulation, and then it has been converted into a much slower intensity fluctuation in the Brillouin laser beam because of the relatively long lifetime of the acoustic wave that is associated with stimulated Brillouin scattering. Therefore, we attribute the intensity noise reduction at high frequencies to relative long lifetimes for both the acoustic wave and the Brillouin cavity. This is analogous to the explanation for phase noise reduction in Brillouin fiber lasers.[4]

It is interesting to compare the measured pump-to-Stokes RIN transfer functions with the intrinsic intensity noises of both the Brillouin and pump lasers. Figure 6 shows the RIN spectra of the Brillouin fiber laser ($R = 50\%$) and its pump laser without the EO modulation. Obviously, at the resonant frequencies the Brillouin laser RIN is even higher than the pump RIN. This is in contrast with the observations of the pump-to-Stokes RIN transfer functions that were smaller than unity at the resonant frequencies for this Brillouin laser. This fact indicates that the intensity noise of Brillouin fiber lasers at the resonant frequencies are dominated not by pump noise transfer but by side mode noise itself, which is the result of amplified spontaneous scattering noise at nonoscillating modes, just like amplified spontaneous emission noise in conventional lasers.

In conclusion, the pump-to-Stokes RIN transfer function has been studied in all-fiber Brillouin ring lasers. Our experimental results are qualitatively in agreement with previous theoretical predictions. In the high-frequency region, as much as 40–60 dB RIN reduction has been confirmed experimentally at the antiresonant frequencies. Even at resonant frequencies the transfer functions were still much lower than unity.

J. Geng's e-mail address is geng@npphotonics.com.

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