Towards Micro-Hz Fundamental Linewidth Fiber Brillouin Laser

Shihan Liu, Yanping Yang, Wenjing Zhang, Zhengyuxiao Yang, Jiahao Hu,
Tong Lin, Haocheng Ke, Yanlan Xiao, Yong Geng, and Heng Zhou
Nonlinear Optics Laboratory
University of Electronic Science and Technology of China, Chengdu 611731, China

Abstract— The laser fundamental linewidth is theoretically defined by the Schawlow-Townes equation [1]:

$$\Delta\upsilon_{ST} = \frac{\hbar\omega^3}{4\pi Q_T Q_E P}(N_T + 1) \tag{1}$$

Herein Q_T and Q_E denotes the total and external quality factor of the laser cavity, P is the output laser power, ω the laser's angular frequency, $\hbar$ the Plank coefficient. N_T denotes the number of thermal quanta in the laser mode and is negligible at optical frequency. Basically, $\Delta\upsilon_{ST}$ (equivalently the white frequency noise) roots in the quantum noise limited random variances of the gain and loss of a laser oscillator [1]. Conventional semiconductor lasers have $\Delta\upsilon_{ST}$ on the kHz to MHz level, while fiber lasers generally offer much smaller $\Delta\upsilon_{ST}$ on the kHz to Hz level. Although $\Delta\upsilon_{ST}$ alone does not represent the overall laser characteristics, it is interesting and potentially-useful to reflect how to access the ultimately achievable small $\Delta\upsilon_{ST}$ of a laser. Here we demonstrate a strategy towards implementing micro-Hz (μHz) fundamental linewidth via fiber Brillouin laser.

Fiber Brillouin laser uses stimulated Brillouin scattering to provide gain and balance the loss of the host fiber cavity. The theoretical Schawlow-Townes-like fundamental linewidth of a Brillouin laser is [1]:

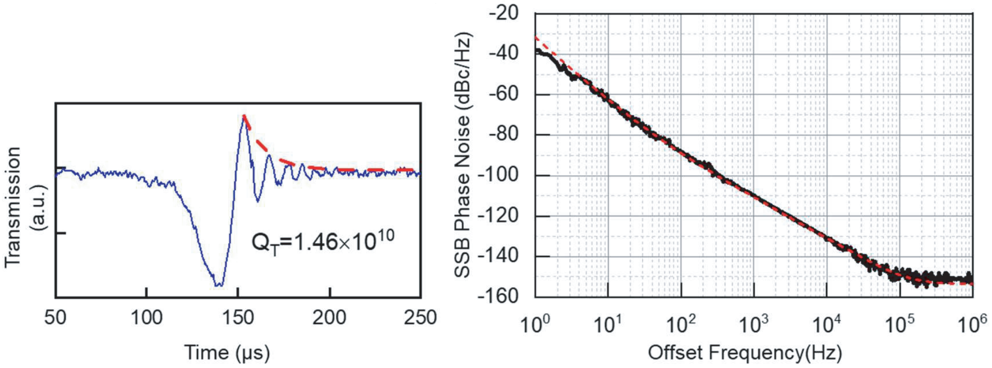
$$\Delta\upsilon_{SBL} = \frac{\hbar\omega^3}{4\pi Q_T Q_E P}(n_T + N_T + 1) \tag{2}$$

n_T in Eq. (2) denotes thermal quanta of the phonon mode and approximately equals to 568 for fused silica fiber at room temperature. Eq. (2) implies that Brillouin laser has about 3 orders of magnitude higher fundamental linewidth than canonical $\Delta\upsilon_{ST}$. However, unlike those inversion-based lasers, Brillouin laser i) derives gain from the cavity waveguide itself and needs no extra gain medium, ii) inherently impose phase damping of the pump field, iii) has quite narrow gain bandwidth that facilitates single longitude mode operation without complex mode control, so it is considered as one of the best platforms to build ultra-low noise laser. According to Eq. (2), smaller $\Delta\upsilon_{SBL}$ can be generated from a laser cavity having as big Q_T and Q_E as possible. Optical fiber is one of the least lossy light waveguide with Rayleigh scattering limited attenuation down to 0.15 dB/km, which translates to an intrinsic quality factor as high as 1.2×10^{11}. Although out coupling and parasitic losses (e.g., nonreciprocal apparatus inside the cavity) usually degrade the actual quality factor, fiber cavity still offers much bigger Q_T than other laser cavities. Fig. 1(a) shows the measured transmission of a homemade standard single mode fiber cavity, the ring down envelop implies that it has $Q_T = 1.46 \times 10^{10}$. We then pump this fiber cavity use a fiber laser (40 mW, 1550 nm) and observe backward Brillouin lasing with estimated output power $P \sim 2.0$ mW. Substituting these values into Eq. (2) predicts that the generated Brillouin laser has a fundamental linewidth $\Delta\upsilon_{SBL} = 12.1$ μHz. To measure the actual $\Delta\upsilon_{SBL}$, we adopt bichromatic pump scheme and generate two Brillouin laser within the same fiber cavity [2], so that the common-mode noise as well as mechanical and vibration noise are suppressed. The measured single-sided phase noise of 15 GHz beat signal between the two common-cavity Brillouin lasers is shown in Fig. 1(b), which is fitted with polynomial phase noise model [3]:

$$S_\varphi(f) = 4.4 \cdot 10^{-16}\,\mathrm{Hz}^{-1} + \frac{8.0 \cdot 10^{-6}\,\mathrm{Hz}}{f^2} + \frac{4.7 \cdot 10^{-4}\,\mathrm{Hz}^2}{f^3} + \frac{2.0 \cdot 10^{-4}\,\mathrm{Hz}^3}{f^4} \tag{3}$$

Assuming two Brillouin lasers have identical linewidth, we obtain that for each laser the fundamental linewidth $\Delta\upsilon_{SBL} = 12.56$ μHz, in good agreement with theory. Eq. (3) implies that higher offset noise (> 100 Hz) mainly consists of white frequency noise, while at closer offset the flicker noise predominates. Prior studies suggest that flicker noise is prone to be caused by thermal fluctuation [3], but still to be scrutinized.

The demonstrated µHz Brillouin lasers are favorable for broadband frequency synthesize. As shown in Fig. 1(b), the 15 GHz microwave produced by two µHz Brillouin lasers exhibits excellent phase noise (e.g., −111 dBc/Hz@1 kHz, −132 dBc/Hz@10 kHz, −149 dBc/Hz@1 MHz), which already levels with state-of-art high-end electronic synthesizers. More importantly, thanks to the high angular frequency ω ($\sim 2\pi \times 193\,\mathrm{THz}$ for NIR lasers), Brillouin lasers with several GHz to several THz frequency interval should have largely identical $\Delta\upsilon_{SBL}$, thus the synthesized signals (microwave to mmWave to THz) could have equally good phase noise independent of their carrier frequency (assuming negligible photodiode noise) [4]. Such µHz Brillouin lasers are also capable to serve as the dual-color references for optical frequency division, enabling ultra-low phase noise photonic microwave oscillators [5].



(a) (b)

Figure 1: (a) Transmission across one resonance of our fiber cavity, the ring down envelop shows $Q_T = 1.46 \times 10^{10}$. (b) Measured phase noise of the 15 GHz beating signal between two common-cavity Brillouin lasers. Red dashed line is the fitting curve calculated from Eq. (3).

REFERENCES

1. Suh, M.-G., Q. Yang, and K. J. Vahala. "Phonon-limited-linewidth of brillouin lasers at cryogenic temperatures," *Physical Review Letters*, Vol. 119, No. 14, 143901, 2017.
2. Loh, W., S. Yegnanarayanan, F. J. O'Donnell, and P. W. Juodawlkis, "Ultra-narrow linewidth Brillouin laser with nanokelvin temperature self-referencing," *Optica*, Vol. 6, No. 2, 152, 2019.
3. Kittlaus, E. A., D. Eliyahu, S. Ganji, S. Williams, A. B. Matsko, K. B. Cooper, and S. Forouhar. "A low-noise photonic heterodyne synthesizer and its application to millimeter-wave radar," *Nature Communications*, Vol. 12, 4397, 2021.
4. Heffernan, B. M., J. Greenberg, T. Hori, T. Tanigawa, and A. Rolland, "Brillouin laser-driven terahertz oscillator up to 3 THz with femtosecond-level timing jitter," arXiv:2311.10214, 2023.
5. Li, J. and K. J. Vahala. "Small-size, ultra-low phase noise photonic microwave oscillators at X-Ka bands," *Optica*, Vol. 10, No. 1, 33, 2023.