Frequency Modulated Integrated 780 nm Brillouin Laser with 24 Hz Fundamental and 1.4 kHz Integral Linewidths and 22 kHz Modulation Bandwidth

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Abstract: We demonstrate a frequency modulated 780 nm Brillouin laser pumped by a semiconductor laser. We achieve a 1.4 kHz 1/π integral linewidth and 24 Hz fundamental linewidth and a 22 kHz modulation bandwidth.

1. Introduction

Integrated narrow-linewidth lasers in the near-IR and visible wavelength range are important for next-generation atomic systems for quantum sensing [1], navigation [2], and precision timekeeping [3,4]. These applications demand exceptional frequency noise characteristics, narrow fundamental and integral linewidths, and agile laser frequency control with respect to atomic transitions that maintains spectrally pure frequency noise characteristics [5]. Laser frequency noise can be reduced by Pound-Drever-Hall (PDH) locking to an ultra-stable table-scale Fabry-Pérot vacuum-spaced silicon mirror reference cavity [6]. Miniaturization of these types of lasers has been achieved with self-injection locking using whispering-gallery-mode resonators (WGMRs) [7] and integrated photonics [8], PDH locking to low-FSR coil resonators [9], and with stimulated Brillouin lasers (SBLs) which narrow laser noise at far-from-carrier frequency offsets [10]. Bulk-optic modulators are typically used to further stabilize or control a cavity-locked laser with respect to an atomic transition or to apply sidebands. Compact stabilization schemes have used actuators to tune and modulate the cavity for locking [11] and recently this approach has been extended to integrated devices such as in silicon nitride [12–14]. However, producing ultra-narrow laser linewidth while maintaining frequency modulation capability has been a challenge in integrated devices in the visible and near-IR.

Here we report demonstration of a photonic-integrated 780 nm stimulated Brillouin laser (SBL) that maintains sub-25 Hz fundamental and sub-1.5 kHz integral linewidths with direct frequency modulation at 22 kHz using a thermo-optic controlled, ultra-high-Q photonic integrated cavity. We pump a thermo-optically modulated integrated Brillouin laser resonator with a 780 nm semiconductor laser and measure a minimum frequency noise of 7.6 Hz^2/Hz at 1 MHz offset from carrier corresponding to a fundamental linewidth of 24 Hz. The integral linewidth is reduced from 180 kHz to 1.4 kHz and the heater modulation of over 20 kHz demonstrates potential for multi-stage laser stabilization and real-time atomic hyper-fine transition spectroscopy for atomic and quantum experiments.

2. Experimental results

The approach to directly frequency modulating the ultra-narrow linewidth 780 nm SBL is shown in Fig. 1. The 780 nm DBR laser is used to pump the SBL resonator and a metal electrode on the ring enables direct thermo-optic modulation of the cavity resonance (Fig. 1a). This configuration is used to maintain the ultra-high Q necessary to generate stimulated Brillouin scattering (SBS) and allows for output laser frequency tuning and modulation while maintaining superb frequency noise properties. The SBL cavity is a 5.84 mm radius resonator, designed with a 5.456 GHz FSR which is phased matched to four times the Brillouin gain shift of 21.8 GHz at 780 nm [15]. The SBS threshold for S1 is 0.9 mW and the S1 is ~15 dB above the pump when operating near S2 threshold. The device is fabricated in a CMOS foundry and consists of a 15 μm SiO_2 lower cladding, a 40 nm thick and 4 μm wide Si_3N_4 core, 6 μm SiO_2 upper cladding, and 250 nm thick and 100 μm wide platinum electrode (Fig. 1a). The ring-bus coupling gap is designed to couple the fundamental TM mode. We measure a Q_i = 118 M, Q_L = 57 M, and propagation loss 0.44 dB/m and the metal electrode is used to tune the resonance with linear tuning of 19.5 MHz/mW [14].

The SBL is pumped with a commercial 780 nm Photodigm™ DBR semiconductor laser PDH-locked to the resonator using a laser current servo (Fig. 1b). At an on-chip power of ~4 mW the SBS laser is near the S2 threshold which results in the minimum fundamental linewidth [10]. When locked, a waveform generator and a 10x voltage amplifier are used to modulate the metal electrode resulting in a modulation of the locked SBS laser frequency. The SBS output

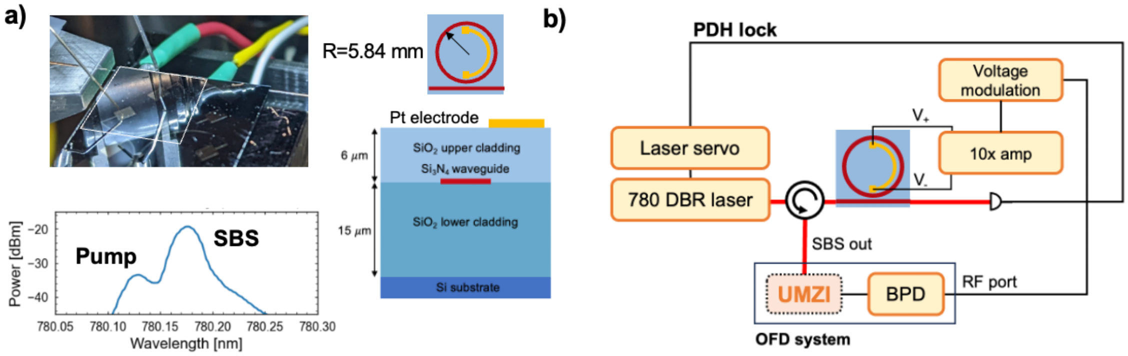

Figure 1. a) Ring resonator device with metal, device layer stack, and stimulated scattering (SBS) measured on an OSA. The ring radius is 5.84 mm and the Brillouin gain shift is 21.8 GHz. b) Pound-Drever-Hall (PDH) laser stabilization schematic used to pump 780 nm SBS. The SBS output is measured with the optical frequency discriminator (OFD) frequency noise measurement system consisting of an unbalanced MZI (UMZI). The resonator is modulated with a waveform generator voltage source during frequency noise measurements.

(power 0.2 mW) is measured with an unbalanced MZI (UMZI) optical frequency discriminator (OFD) and the RF output port of the balanced photodetector measures the fast modulation of the laser frequency. The frequency modulation response is shown in Fig. 2a and the bandwidth of the modulation, determined by the 180° phase lag point, is f_{180° = 22 kHz. The same OFD measurement is used to measure the laser frequency noise system (described in detail in [10]) to extract the SBL linewidth. The high Q and the good overlap of the Brillouin gain profile and resonator FSRs results in a strong reduction in the laser frequency noise at frequency offsets above 1 kHz (Fig. 2b). For the best SBS measurement (green trace), the free-running laser 1/π integral linewidth is reduced from 180 kHz to 1.4 kHz. The fundamental linewidth is reduced from 33 kHz to 24 Hz, a reduction of over 30 dB. During these measurements, the metal electrodes are modulated at 15, 25, and 35 kHz at 250 mVpp and at 50 kHz at 2 Vpp. The spurs of the OFD frequency noise indicate that the bandwidth of the modulation can reach over 30 kHz. The discrepancy in the minimum fundamental linewidth during these traces is related to fluctuations in the on-chip power and pump light leakage into the frequency noise measurement system.

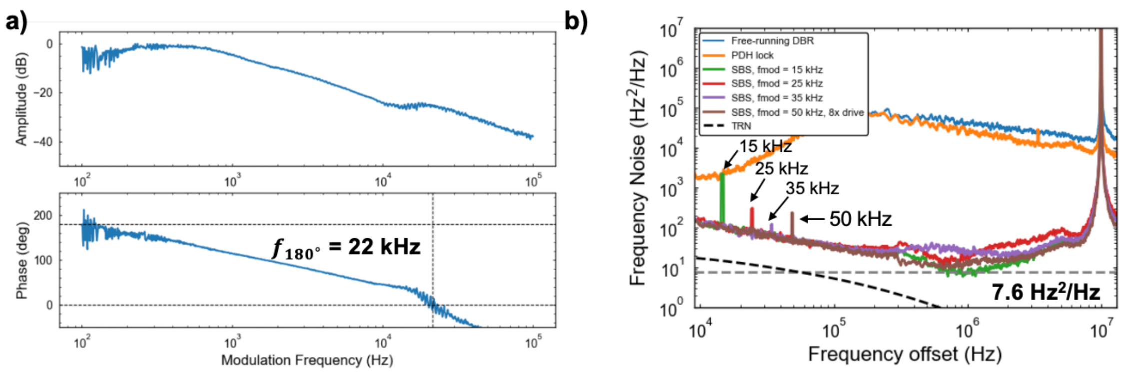

Figure 2. a) SBS laser frequency response measurements by modulating the thermal tuner and measuring the RF port of the balanced photodetector signal from the UMZI. b) Frequency noise acquired with OFD system for free-running laser, PDH lock only (below SBS threshold), and while pumping SBS with different heater modulation frequencies. For f_{mod}= 50 kHz the drive amplitude is 8 times larger.

3. Conclusion

We demonstrate a frequency modulated, narrow-linewidth 780 SBS laser with a 24 Hz fundamental and 1.4 kHz integral linewidth, capable of frequency modulation of over 20 kHz. The sub-mW SBS threshold enables operation without an amplifier for the 780 nm DBR pump laser. Combined with the large tuning range of the metallized device using a robust PDH lock [14], the fast modulation speed can be used for stabilization to rubidium saturation absorption spectroscopy. The operation can be extended for a 2-photon rubidium atomic clock at 778 nm, where the short-term clock stability may be limited by laser frequency noise at frequency offsets 50-100 kHz due to the intermodulation noise effect [4,5]. Fast, agile laser frequency control can be used for laser stabilization in photonic-integrated cold atom experiments [15] for different cooling sequences and beat-note stabilization to enable next-generation compact atomic systems.

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