Photonic integrated cascade-inhibited Brillouin laser with sub-100-mHz fundamental linewidth

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Abstract: We report a photonic-molecule-like waveguide resonator to suppress high order Stokes emissions, achieving only the first order Stokes emission and a fundamental linewidth of 71 mHz with 10mW output power.

1. Introduction

Photonic integrated sub-hertz linewidth lasers are of interest for a wide range of precision scientific and commercial applications, including coherent communications [1], atomic and quantum sensing [2], and atomic clocks [3]. The stimulated Brillouin scattering (SBS) laser has the unique capability to narrow the pump laser fundamental linewidth by many orders of magnitude, leading to significant high frequency noise reduction [4]. A 1550 nm photonic integrated SBS laser based on a silicon nitride waveguide ultra-high-Q resonator with a 10.4 mW threshold power and 0.72 Hz fundamental linewidth was demonstrated [5] and the technique applied to a 674 nm/698 nm integrarted SBS laser [6]. However, the fundamental linewidth of these lasers is limited by their cascaded emission property as the threshold for each Stokes order is reached [7], limiting the photon population for each order and providing quantum noise feedback from higher to lower orders. Laser resonator designs that can suppress higher order Stokes emission overcomes this limit and allows the first order Stokes (S1) to continue increasing in power and further narrow the linewidth using grating modulated resonator waveguides [8] or different waveguide modes [9]. However, these approaches have various limitations; for example, the grating modulated waveguides suffer from excessive waveguide loss from the gratings.

In this paper, we report a single Stokes (S1) SBS laser constructed with a novel photonic-molecule-like waveguide resonator to suppress the emission of second order Stokes (S2) and higher using the coupled-mode resonator splitting. We demonstrate a non-cascaded SBS laser with a measured threshold of 2.3 mW and measure a fundamental linewidth of 71 mHz and output power of 10 mW. The nested ring design can translate to other wavelengths from visible to IR.

2. Photonic-molecule resonator design and SBS laser

Our design of ultra-high-Q Si_3N_4 waveguide (11 μm by 40 nm) and SBS resonator is described in [5,10]. Here, we utilize, for the first time, a photonic-molecule-like double-ring structure (Fig. 1(a)) that creates coupling between different modes such that the S2 frequency shift is inhibited through resonance splitting but the S1 frequency shift stays in-tact. The S1 resonance is located 4 FSRs away from the split resonance (Fig. 1(c)), which is S2 is located at and suppressed by. The split resonance is measured to have a splitting of 198 MHz and a loaded Q of ~11 Million, while the non-split resonance Q is measured to be 164 Million intrinsic and 92 Million loaded around 1570 nm (Fig. 1(d)). Q measurements are made using a RF calibrated fiber Mach-Zehnder interferometer (MZI) technique [5].

To drive the SBS S1 Stokes, we lock a widely tunable laser (Velocity™ TLB-6700) to the non-split resonance using the Pound-Drever-Hall technique [21], with S2 aligned to the split resonance (Fig. 1(b)). Measurement of the emission on an optical spectrum analyzer (OSA) (Fig. 2(d)) shows no presence of S2 or higher order Stokes as the pump power increases. A fiber MZI optical frequency discriminator (OFD) is used for self-delayed homodyne laser frequency noise measurement [5] and the fundamental linewidth $\Delta\nu$ is given by the white-frequency-noise floor times π. The frequency noise of S1 at different pump powers (Fig. 2(a) and 2(c)) demonstrates linewidth narrowing. The S1 minimum $\Delta\nu$ reached 71 mHz, corresponding to a white frequency noise of 23 mHz^2/Hz. We calculate the transferred pump frequency noise limited linewidth to be 62 mHz (yellow dash in Fig. 2(c)), using the formula in [4] and the thermorefractive noise (TRN) limit for this resonator is shown in Fig. 2(a) as the dashed green.

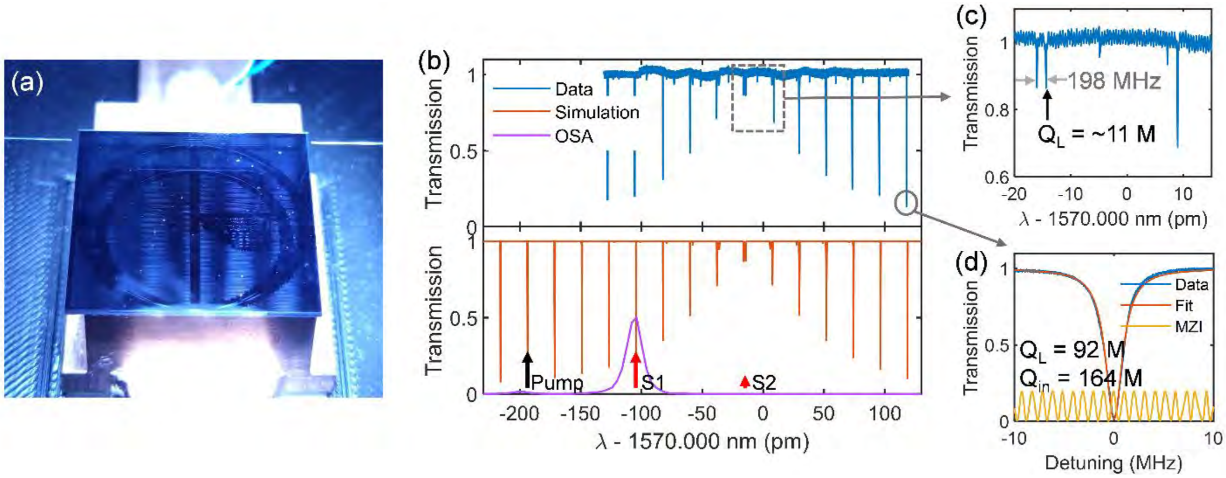

Fig. 1. Non-cascaded SBS laser design. (a) Double-ring resonator device picture. (b) Transmission spectrum shows one split resonance and other non-split resonances near 1570 nm. (c) Zoom-in of the split resonance. (d) Q and linewidth measurement of the high-Q non-split resonance.

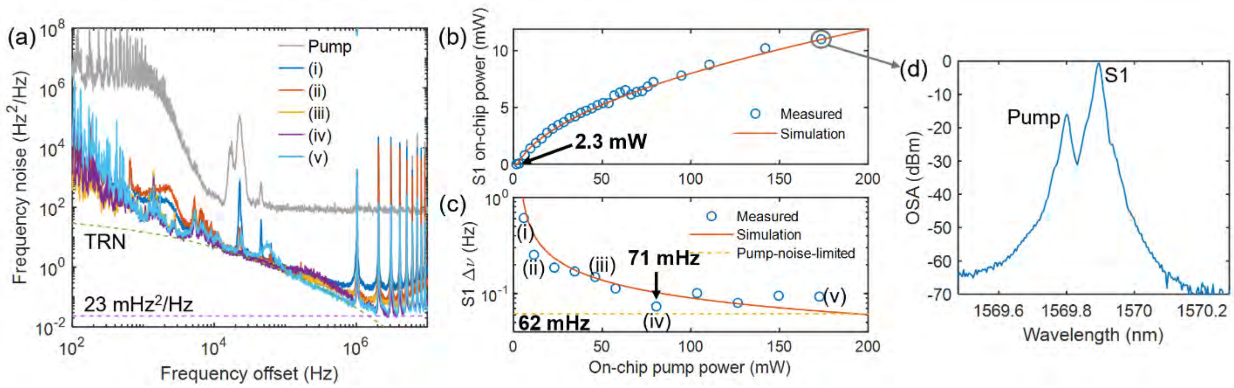

Fig. 2. Non-cascaded SBS laser threshold and fundamental linewidth measurement. (a) OFD frequency noise spectra at different power powers. (b) S1 on-chip power versus on-chip pump power shows the 2.3 mW threshold. (c) Fundamental linewidth narrows with increasing pump power. (d) OSA power spectrum shows the suppression of S2.

3. Conclusion

In this paper, we report a novel photonic-molecule-like waveguide resonator that suppresses SBS S2 and higher order Stokes emission using coupled-mode resonance splitting. Using this design, we achieve record low non-cascaded SBS fundamental linewidth of 71 mHz (correspond to a white frequency noise of 23 mHz^2/Hz) and a 2.3 mW S1 threshold and output power of 10 mW. In the future, lower lasing threshold and higher output power can be achieved with reduced waveguide propagation loss and increased resonator Q; combined with overcoming the pump noise limitation, much narrower fundamental linewidth even below 10 mHz can be possible.

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