Reducing Noise in a Ring-laser Gyro Based on Stimulated Brillouin Scattering

Karl D. Nelson[1], Matthew W. Puckett[1], Jianfeng Wu[1], Debapam Bose[2], Sarat C. Gundavarapu[2], Daniel Blumenthal[2]
[1]Honeywell Aerospace, Plymouth, MN and [2]Uuniversity of California at Santa Barbara, USA

Although Brillouin scattering is a parasitic effect in many systems, stimulated Brillouin scattering (SBS) can also be harnessed for useful applications. Brillouin lasers have been of interest in the fields of optics and photonics since the early 1990s because of the extremely narrow linewidths they offer [1]. Chip-scale versions of these devices have begun to emerge more recently, and the performance attained in them is steadily approaching that of their fiber counterparts [2-4]. Honeywell is using Brillouin lasing in chip-scale SiO_2/Si_3N_4 waveguide resonators to create a robust ring-laser gyroscope. Current limitations on gyro noise are 1) limited optical power in the sensing light, due to cascading of Brillouin lasing to higher SBS orders, and 2) scattering and absorption loss of the Brillouin light in the resonator. We are addressing both issues.

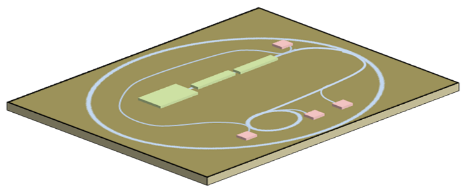

Figure 1. Rendering of an optical-waveguide-based ring-laser gyro. The optical waveguide is formed as a circular resonator on a silicon chip with lasers, filters, and detectors within. Approximately one inch per side.

The basic operation of the SBS ring-laser gyro is as follows: A pump laser is introduced into a ring resonator on resonance so that a high optical intensity is built up in the resonator. The free spectral range (FSR) of the resonator is designed to be a multiple of the Brillouin shift in the waveguide medium (about 11 GHz in our resonators). The high circulating pump intensity creates counter-propagating circulating light via SBS, red-shifted by 11 GHz, which is in turn enhanced by the resonator. Cascaded (2nd-order) SBS is also stimulated when the circulating 1st-order SBS power is sufficient; this 2nd-order light co-propagating with the pump light and red-shifted by 22 GHz. The co-propagating pump and 2nd-order light form a frequency reference at 22 GHz via the beat frequency between them which is insensitive to rotation but tracks the temperature and other variations of the resonator. The counter-propagating pump and 1st-order light (or 1st-order and 2nd-order) form a rotation-sensitive beat frequency at 11 GHz. When compared to the 22 GHz reference, the rotation-sensitive signal has many noise sources common-mode with the reference frequency and therefore that noise is not present on the rotation signal. The counter-propagating beat frequency shifts with rotation via the Sagnac effect as with any ring-laser gyro.

Good gyro performance, especially low angle random walk (ARW), is achieved by lowering the linewidth of the light fields generating the signal. A high-Q resonator allows the pump linewidth to be narrowed by locking the pump to the resonance. SBS orders are narrowed further by the physical processes associated with SBS. Resonator Q can be enhanced by lower optical losses (such as, those due to scattering) in the optical waveguide. However, SBS linewidth is still tied to the optical intensity via the Schawlow-Townes relation, as with any coherent source.

The cascading higher-order Stokes (red-shifted) waves (made possible by the required alignment of our resonator FSR to the SBS frequency shift) limit the ability to increase power in the desired orders. Additional pump power goes into higher-order SBS rather than into higher 1st-order power. This limited power translates, through the Schawlow-Townes relation, to a limit on the minimum linewidth that can be attained in a Brillouin laser [5], in turn limiting gyro performance.

We have previously demonstrated Brillouin lasing in a high-Q ring resonator [4]. Cascaded Brillouin lasing was observed up to the 10th-order Stokes wave, and although this was in itself an impressive result, it results in low efficiency when the objective is to achieve low phase noise by increasing power solely in the 1st-order Stokes wave. This solution is to block the means by which power couples from the desired Stokes wave to the next-higher-order mode.

For example, in steady-state, and assuming that the pump power is below the threshold for 3rd-order Brillouin lasing, the relationships among the circulating pump, 1st-, and 2nd-order Stokes photon numbers are given by the following equations [5]:

$$p_0 = \frac{p_p Q}{2\omega} \quad (1)$$

$$p_1 = \frac{\omega}{Qg} \quad (2)$$

$$p_2 = \frac{p_p Q}{2\omega} - \frac{\omega}{Qg}, \quad (3)$$

978-1-5386-7828-2/19/$31.00 ©2019 IEEE

where p_0, p_1, and p_2 are the circulating photon numbers, Q is the quality factor of the resonator, ω is the angular optical frequency, p_p is the rate at which pump photons enter the resonator, and g is the Brillouin gain coefficient. The existence of the 2nd-order Stokes wave is the cause of the constant (non-p_p-dependent) Eq. 2. The 1st-order Stokes power is insensitive to increased pump power in this regime, as is its linewidth. In contrast, when pump power is subthreshold for 2nd-order Brillouin lasing, the powers are described by [5]:

$$p_0 = \frac{\omega}{Qg} \quad (4)$$

$$p_1 = \frac{p_p Q}{\omega} - \frac{\omega}{Qg}. \quad (5)$$

In this regime, the 1st-order Stokes power increases monotonically with the pump power. In this example, suppose we determine to extend the range of this regime, in which the 1st-order power remains proportional to pump power. This could be done by increasing the *loss* in the resonator for 2nd-order Stokes, which increases the 2nd-order threshold. This can be understood by realizing that if loss is high for the 2nd order, the power cannot build up sufficiently to create the acoustic grating that is responsible for scattering light from the 1st order to the 2nd order.

We increase the loss for undesired orders by including a Bragg grating in the resonator. In a resonator with an incorporated grating of period Λ, the optical resonance at wavelength 2Λ will be split into two resonances as shown in Figure 2.

We design the split resonance to correspond to the lasing frequency of the lowest-order undesired Stokes wave, ensuring that no cavity resonance overlaps with the frequency of that order. Without cavity enhancement, the threshold is extended beyond reach and optical power in the desired Stokes waves can increase beyond the former limit.

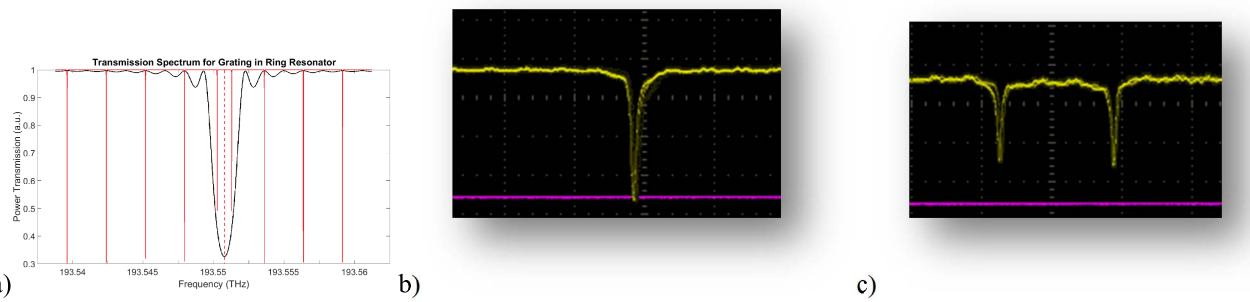

Figure 2. a) Transmission spectra of (black) a 74 mm-long Bragg grating in a silicon nitride waveguide and (red) of a ring resonator formed out of the same Bragg grating and critically coupled to a bus waveguide. In the absence of the index perturbation caused by the grating, there would be a resonance along the dashed red line. b) Oscilloscope trace of an unperturbed resonance. c) Oscilloscope trace of the perturbed resonance showing the dual peaks, both shallower and shifted from the expected position.

We combine Eqs. 4 and 5 with the known expression for the linewidth of a Brillouin laser [5], and using the reported loss and gain coefficients for our waveguides [4], show that, as expected, when the 2nd-order Stokes wave is suppressed, the power in the 1st-order Stokes wave increases monotonically with the pump power (Figure 3a). This predicts linewidth values as low as 36 mHz for a pump power of 1 W, which will translate to correspondingly lower gyro noise.

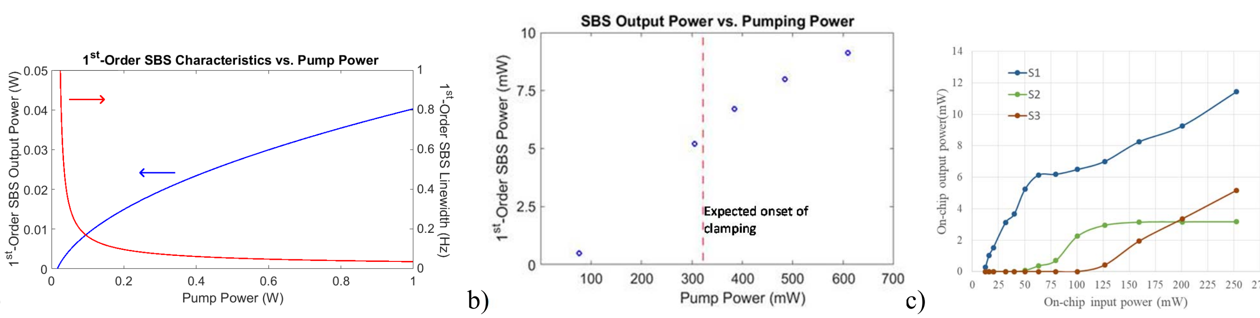

Figure 3. a) Calculated 1st-order SBS characteristics of a silicon nitride ring resonator in terms of output power (red) and linewidth (blue) in the absence of 2nd-order SBS as a function of pump power. At a pump power of 1 W the output SBS power is 40 mW and the laser linewidth is 36 mHz. b) Measured power in the 1st-order SBS as a function of pump power. The expected onset of SBS is marked. c) SBS power (for three SBS orders S1, S2, and S3) vs. pump power for a simple resonator, showing the clamping thresholds as described by equations 1-3, shown as a contrast to the results in (b).

As mentioned above, reduced scattering loss is also important to lower the ARW of the gyro, and it is important that the incorporated Bragg grating not increase the optical loss. We have measured the linewidth of an unperturbed resonance in our grating resonator and calculated the corresponding optical loss by fitting the lineshape to the function

$$T = \left(\frac{t^2 - 2t\tau\cos\left(\frac{4\pi^2 n_{\text{eff}} \Delta f r}{c}\right) + \tau^2}{1 - 2t\tau\cos\left(\frac{4\pi^2 n_{\text{eff}} \Delta f r}{c}\right) + t^2\tau^2} \right) \quad (6)$$

where t is the field transmission across the resonator's coupler, τ is the field retention across one round trip within the resonator, r is the resonator's radius, Δf is the frequency detuning, n_{eff} is the effective index of the resonator waveguide, and c is the speed of light. The results this process yields are shown in Figure 4. Importantly, a full-width half-maximum (FWHM) of 1.76 MHz, corresponding to a propagation loss of 0.123 dB/m, is measured at the pump wavelength of 1563 nm. To the best of the authors' knowledge, this represents a new record-low loss value in a chip-scale waveguide. This low optical loss allows us to observe SBS with only 10 mW of on-chip optical power, again a record-low value for this type of resonator.

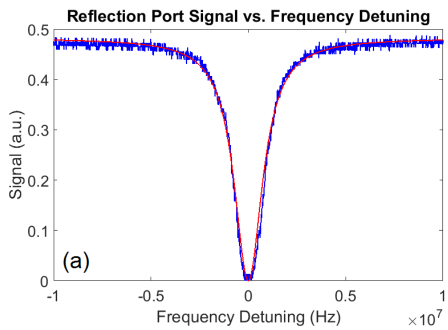

Figure 4. Transmission spectrum of one resonator at an optical wavelength of 1563 nm (blue) along with a Lorentzian fit to the data (red), which yields a propagation loss value of 0.123 dB/m.

By combining the grating resonator and ultra-low-loss waveguide into an SBS ring-laser gyroscope as described above, we expect to achieve ARW less than 0.01 degrees per root-hour.

Acknowledgement: This material is based upon work supported by the Defense Advanced Research Projects Agency (DARPA). The views and conclusions contained in this document are those of the authors and should not be interpreted as representing official policies of DARPA or the U.S. Government. Approved for Public Release, Distribution Unlimited

[1] E. Garmire, "Perspectives on stimulated Brillouin scattering," New Journal of Physics **19,** 011003 (2017).
[2] J. Li, "Low-noise Brillouin laser on a chip at 1064 nm," Optics Letters **39**, 287-290 (2014).
[3] H. Shin, "Tailorable stimulated Brillouin scattering in nanoscale silicon waveguides," Nature Communications **4**, 1944 (2013).
[4] S. Gundavarapu, "Integrated Waveguide Brillouin Laser," arXiv (2017).
[5] M. Suh, "Phonon-Limited-Linewidth of Brillouin Lasers at Cryogenic Temperatures," Physical Review Letters **119**, 143901 (2017).