A Chip-Based Brillouin Laser Gyroscope with Earth-rotaton-rate Sensitivity

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Abstract: The physical principles of a chip-based Brillouin laser gyroscope are reviewed. The device can resolve sinusoidal rotations with amplitude as low as 5 degrees/hour and is also used to detect the Earth's rotation. © 2021 The Author(s)

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Counter-propagating lightwaves within a closed rotating loop enable rotation measurement as a result of the Sagnac effect [1]. And modern optical gyroscopes use long coiled optical fiber paths (fiber optic gyroscopes [2]) or resonant recirculation (ring laser gyroscopes [3]) to greatly enhance this effect. In recent years, the possibility of chip-based optical gyroscopes has garnered considerable attention. Such integrated optical gyrocopes could enjoy the advantages of integration and scalable manufacturing, and would offer rugged designs for operation in challenging environments [1]. Compact or chip-based ring laser gyroscopes [4–6], passive resonant gyroscopes [7–10], and interferometric gyroscopes [11] have been reported. Here we review the operation of a chip-based Brilloun laser gyroscope that has been used to measure the Earth's rotation [6].

The device uses 36mm and 18 mm diameter high-Q whispering-gallery silica resonators fabricated on silicon [12] (Fig. 1a). By pumping the resonators along clockwise (CW) and counter-clockwise (CCW) directions, generation of counter-propagating (CP) laser waves within the same cavity mode (Fig. 1b) is possible. By slightly detuning the frequencies of the two pumping waves (which themselves are derived from a single laser), the CP laser frequencies can be slightly detuned so as to produce an audio-rate beat frequency upon their detection. This detuning results from directional-dependent dispersion induced by the Brillouin phase-matching process, and it is essential to the gyroscope's operation. Specifically, optical back-scattering couples CW and CCW waves and creates a rotation dead band similar to that observed in commercial (non-chip) ring laser systems. Here, the nonzero pump detuning in the range of 1 MHz ($\Delta\nu_p$) introduces dispersion that pulls the CP lasing frequencies apart so as to unlock the gyro readout ($\Delta\nu_s$) (Fig. 2a). The gyro readout beat frequency has a sub-Hertz linewidth because of the high optical Q factor of the resonator [13]. Moreover, co-lasing of the clockwise and counter-clockwise Stokes waves suppresses common-mode drift in the beat signal [13]. The Allan deviation of the gyro shows $0.068^\circ/\sqrt{\mathrm{h}}$ angular random walk (ARW) and $3.6^\circ/\mathrm{h}$ bias stability when using a 36 mm diameter resonator. A smaller diameter resonator (18 mm) was also measured to characterize the effect of resonator area and mode volume on performance.

The performance of the gyroscope was tested by applying an external sinusoidal rotation similar to the configuration in Ref. [4]. The gyroscope achieves a rotation amplitude sensitivity as low as $5^\circ/\mathrm{h}$ (Fig. 2b). As

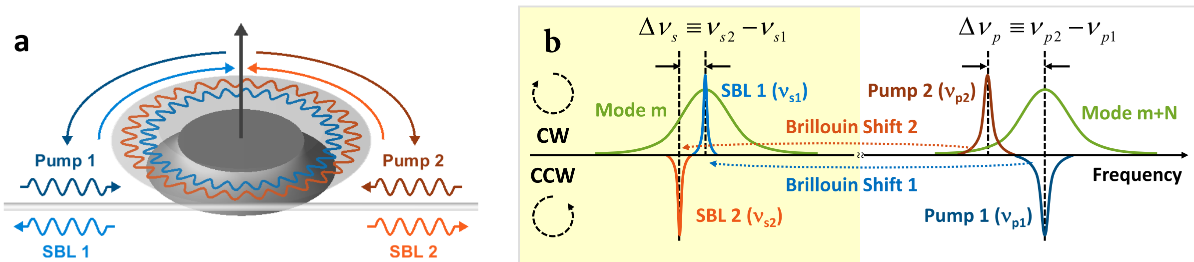

Fig. 1. **Operating principle of the counter-pumped stimulated Brillouin laser gyroscope. a**, The circulation directions of the pumps and their corresponding stimulated Brillouin laser (SBL) waves. **b**, Spectral diagram of offset counter-pumping. The nonzero pump detuning ($\Delta\nu_p$) unlocks the gyro readout ($\Delta\nu_s$) through Brillouin gain induced dispersion.

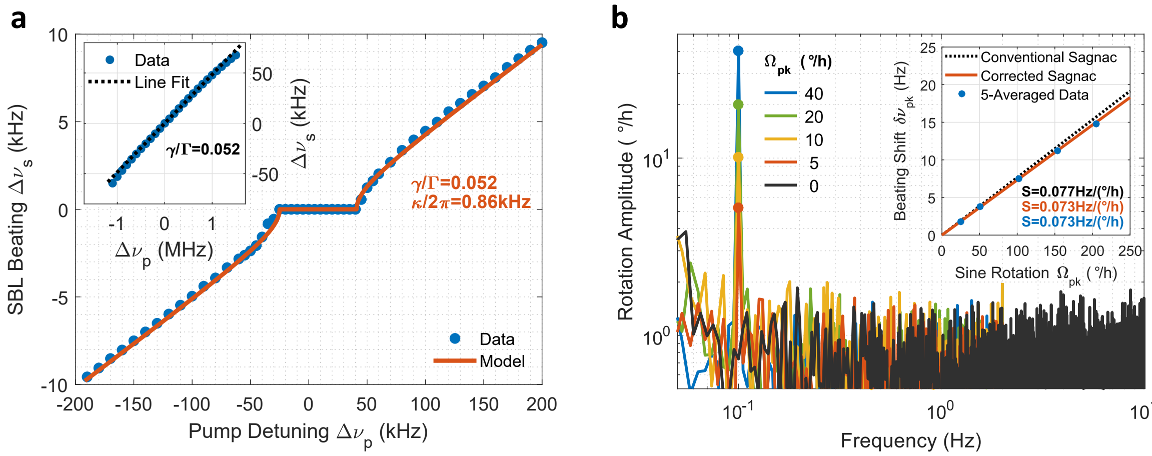

Fig. 2. **Unlocking the gyroscope and sinusoidal rotation measurement. a**, Measured beat frequency of the CW and CCW laser waves is plotted versus the pump frequency detuning without rotation (blue points). Red curve is a model with fitting parameters given in the legend (γ, Γ, κ are cavity mode damping rate, Brillouin linewidth, and back-scattering rate). Inset gives the same data, but over a wider range of pump detuning frequencies. **b**, The fast Fourier transform spectrum of the 36mm-gyro readout under sinusoidal rotation at 0.1 Hz. The spectral peaks at 0.1 Hz resolve a series of different modulation rate amplitudes (see Legend). The minimum resolved amplitude is 5°/h. Inset: zoom-in of the gyroscope signal.

an additional test, the Earth's rotation was measured by switching the gyroscope axis between North and South directions. This is the first time that the Earth's rotation has been measured using a chip-based optical gyroscope. The results are encouraging for the development of chip-based laser gyroscopes in general.

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