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Ultra-narrow linewidth Brillouin laser with nanokelvin temperature self-referencing: supplementary material

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I. Resonator frequency shift with temperature

In any resonator system, shifts in the resonance frequency (v) are related to refractive index (n) shifts and length (L) shifts by

$$\frac{dv}{v} \approx -\frac{dn}{n} - \frac{dL}{L} \tag{S1}$$

Both the refractive index and length are temperature dependent, which is made explicit in Eq. (S1) by including effects of thermoexpansion (α) and thermally-induced changes in refractive index (dn/dT)

$$\frac{dv}{v} \approx -\frac{1}{n}\frac{dn}{dT}\Delta T - \alpha\Delta T \tag{S2}$$

For the material of silica glass comprising the core of our fiber resonator, $\alpha = 0.51\times10^{-6}$ 1/K and $dn/dT = 11.6\times10^{-6}$ 1/K, which combined with $v = 193.6\times10^{12}$ Hz and $n = 1.45$ yields a 1.65 GHz shift in resonance frequency for a 1 °C shift in temperature.

II. Temperature stabilization of SBS laser

We utilized both passive and active temperature stabilization to reduce the drift of our SBS laser system. Our passive temperature stabilization consisted of a plexiglass enclosure resting on a floating optical table which isolates our SBS laser from environmental fluctuations. For active temperature control, we stabilized the SBS laser's temperature by first detecting the frequency of the dual-polarization SBS beat using a frequency counter. This measurement was then monitored on a computer, which use a software PID feedback loop to drive the voltage sent to a resistive heater for control of the resonator's temperature. The heater is pinned down

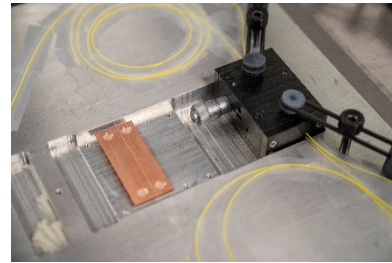over a section of the resonator's bare fiber which is resting on

Fig. S1. Picture of the SBS resonator with a section of bare fiber stretched over a copper plate (resistive heater not shown).

top of a copper plate (Fig. S1). A thermistor attached to this copper plate was also utilized to independently monitor the resonator temperature. The loop time constant was set to 0.5 s to prevent oscillation instability and to allow for SBS drift correction for Fourier frequencies below 1 Hz. This slow loop time constant also enables the SBS laser to maintain its excellent noise characteristics above 1 Hz frequency.

III. Pump-SBS equivalence for temperature locking

Previous implementations of the dual-polarization temperature sensing technique have traditionally utilized two separate lasers locked to the two orthogonal polarization modes of a resonator. A measurement of the resulting beat note generated by the two locked lasers directly provides a measure of the residual shifts in the resonator temperature. By adapting this scheme for the use of two orthogonal polarization stimulated Brillouin scattering (SBS) lasers, we are able to improve the resolution of this technique through the inherently lower noise provided by the narrow SBS laser linewidth. However, it is not immediately clear that the SBS beat-note response to temperature will be directly equivalent to the beat-note response of the locked lasers for sensing temperature.

Figure S2 shows a measurement confirming this direct correspondence where the resonator temperature of an SBS laser is

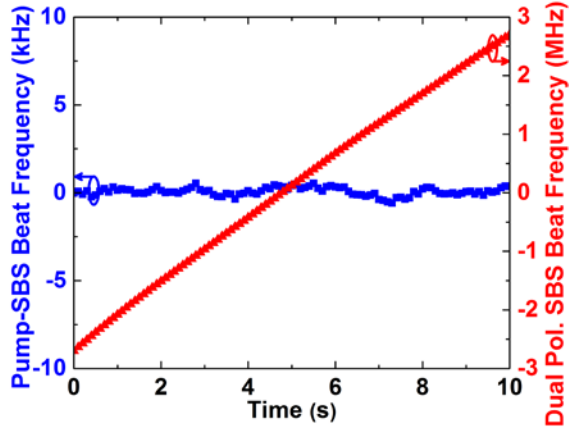ramped by 0.1 °C over 10 seconds. The shift in temperature causes

Fig. S2. Test of equivalence between pump and SBS for temperature sensing. For a temperature shift of 0.1 °C over the course of 10 seconds, the locked pump and SBS laser beat note frequency (blue squares) remains fixed at 0, while the dual polarization SBS beat (red triangles) shifts by 5.4 MHz.

the dual-polarization SBS beat note (red triangles) to shift by 5.4 MHz, while the beat note difference of the locked pump to the SBS (blue squares) remains constant at 0. This measurement confirms that the dual-polarization SBS beat is sensitive to and can be used to measure changes in the resonator temperature. Moreover, this measurement also shows that both the locked pump and the SBS laser shift at exactly the same rate in response to temperature so that their relative frequency difference remains zero. We note that the center frequencies of 30 MHz and 10.9 GHz were removed from the dual-polarization SBS beat and the pump-SBS beat, respectively.

IV. Dual polarization common-mode noise suppression

It is important for the dual-polarization SBS beat to sense only variations in temperature and thus remain insensitive to other noise variations of the resonator. Since many of the noise processes that occur are common mode and shift the frequencies of both SBS laser polarizations equally, these
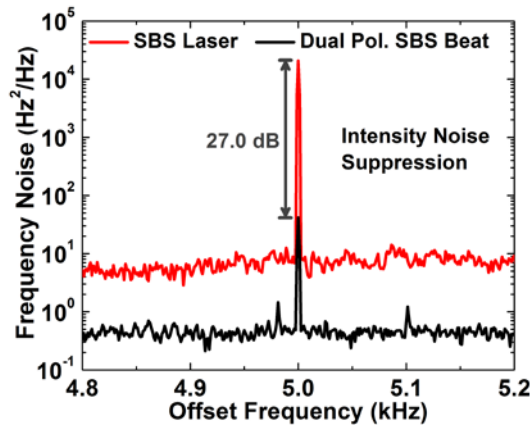

Fig. S3. Suppression of intensity noise when comparing the beat generated by two independent SBS lasers (red) to the beat of two orthogonal polarization SBS lasers residing within a single resonator (black). For a 5 kHz applied modulation to the input pump power, the resulting suppression is 27 dB.
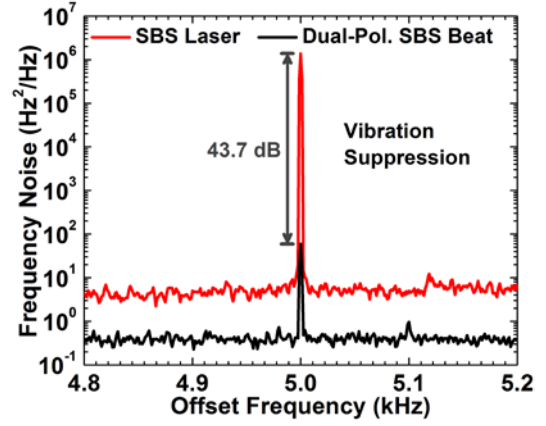

Fig. S4. Suppression of vibration noise for a 5 kHz applied acoustic tone. The common-mode rejection is 43.7 dB.

noise sources largely cancel out in the resulting SBS beat frequency.

Figures S3 and S4 illustrates the magnitude of this common-mode suppression for intensity noise processes and for noise that arises from environmental vibration. Both measurements compare the frequency noise generated by the beat of two independent SBS lasers (red) to the beat note generated by two orthogonal polarization SBS lasers originating from a single resonator (black). In Fig. S3, when a 5 kHz sinusoidal modulation is applied to the input pump power, the dual polarization SBS beat is reduced by 27 dB due to the common-mode noise cancellation of the applied intensity variation. Furthermore, in Fig. S4, when a 5 kHz acoustic tone is applied near the SBS laser, the common-mode suppression of the induced vibration is measured to be 43.7 dB. We note that the intentional choice of 5 kHz is at a sufficiently high frequency to prevent any thermal response from the resonator.

V. SBS laser temperature measurement sensitivity

To prevent environmental temperature fluctuations from influencing our temperature measurement, we utilize a lock-in approach to assess the temperature sensitivity limit of the dual-polarization SBS laser. As described in the main text, we apply a known heater power modulation to the SBS resonator, and the resulting frequency shift of the dual-polarization SBS is converted to a temperature change. Figure S5 shows four measurements of the induced temperature shift when a 1 Hz raised sine modulation is delivered to an 80 Ω resistive heater. The heater power is controlled through a variable attenuator and is successively reduced resulting in measured values of temperature shifts that decrease from 2.1 μK down to 120 nK in Fig. S5. The noise floor of the measurement corresponds to a temperature change of ~70 nK, which corresponds to the sensitivity limit of our SBS laser. The conversion from spectral density units of μK/√Hz to absolute temperature change requires the integration of the measured 1 Hz peak over the square root of the 50 mHz resolution bandwidth. In addition, the root mean square values of spectral density must also be converted to peak-to-peak values to find the total temperature swing along the sinusoidal modulation.
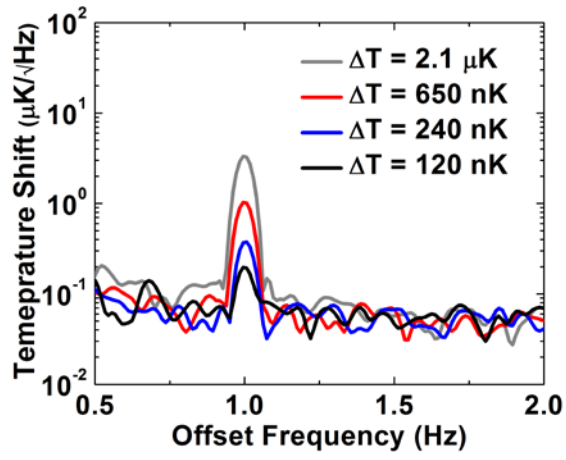
Fig. S5. Measured temperature shifts under 1 Hz applied heater modulation resolved by the SBS laser temperature sensing technique. The 120 nK peak is still apparent compared to the 70 nK noise floor.