Supplemental Document

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Sagnac-witnessed laser deflection is an ultra-sensitive acoustic detector: supplement

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This document contains additional information about the experimental set-up, calibrated pressure measurements, and ray tracing simulations.

1. EXTENDED METHODS

A. Set up

Our probe beam is derived from a 1064 nm continuous-wave laser (Innolight Mephisto, now manufactured by Coherent). A 1/2-wave plate and polarizing-beamsplitter pair reduce the intensity to 60 mW for the experiments reported here. However, operation using just a few hundred microwatts is possible. The beam enters the Sagnac interferometer with a waist of 3 mm through one face of a 50/50 beamsplitter cube. Each beam then traverses a loop comprised of three mirrors before returning to the 50/50 cube. One arm of the loop includes a 1:1 telescope made of two 150 mm focal-length lenses. Acoustic detection is made between the two telescope lenses for enhanced bandwidth. The opposite arm consists of a 1/4-wave, 1/2-wave, 1/4-wave-plate triplet used to control the relative phase between the two beams of the interferometer. At the dark port, we use a Glan-Thompson polarizer to reject any back-scattered light that has not reached the waveplate triplet. Another 1/2-waveplate and polarizing-beamsplitter pair adjusts the light levels for safe and linear photodetection using either a cut mirror and an amplified balanced photodetector (Thorlabs PDB120C) or a single amplified photodiode (Thorlabs PDA10CS). For the data presented in this work, we limit the detected power to 300 µW.

The pulsed excitation laser (Big Sky/Quantel) operates with a flat-top mode shape, a wavelength of 532 nm, a pulse length of 5 ns, a repetition rate of up to 50 Hz, and a pulse energy of up to 200 mJ. The pulse energy may be adjusted using 1/2-waveplate and polarizing-beamsplitter pair and electronic control of the internal flashlamp pump energy. Pulses are focused by a 60 mm focal length lens onto an aluminum block 10 cm from the Sagnac's sensing arm and 10 cm from the reference microphone (GRAS 46 DE 1/8-inch pressure standard microphone).

Alternatively, a 40 kHz piezo buzzer (Murata MA40S4S) placed 1 cm from the Sagnac's active arm and 1.3 cm from the reference microphone, was used for the SNR measurements. The buzzer was driven by a function generator (Agilent 33250A) with a 40 kHz, 1 V peak-to-peak sine wave. For the SNR measuremnts only, the microphone and laser signals were low-pass filtered at 100kHz (Stanford Research Systems SR560) before digitization (GaGe 1622, 16 bits, 25 MHz sampling rate).

B. Pressure calibration

Laser beams deflect up refractive index gradients. Therefore, the laser deflection signals are approximately proportional to the derivative of acoustic pressure. In Fig. 2, we make use of a more refined model for spherical waves [1]. The pressure-to-voltage transfer function is given as

$$H(\ell, f) = A\tau\omega K_1(\tau\omega)e^{\tau\omega}\,, \tag{S1}$$

where K_1 is the order-one modified Bessel function of the second kind, $\omega = 2\pi f$ is the circular frequency, $\tau = r_0/c_0$, r_0 is the minimum distance from the spherical wave's epicenter to the probe beam, and c_0 is the speed of sound. The real-valued calibration constant A is proportional to $-2/n_0$, where n_0 is that static refractive index of the environment, and several factors related to photodetection, including the probe beam's optical power, the detector's responsivity, and the detector's transimpedance gain. We find A empirically by (i) transforming our measured signal using Eq. (S1) and frequency-domain deconvolution, (ii) aligning the trough minima measured by the microphone to that observed in the transformed laser deflection signal, and (iii) finding the scale factor A that best matches the laser signal to the calibrated microphone signal in the vicinity of the trough.

C. Ray tracing simulations

Here we outline custom two-dimensional ray tracing simulations of our Sagnac-enhanced acoustic detection technique. The methods described here were used to produce Fig. 1 (b-c).

The laser beam is modeled as a finite bundle of N rays. Each ray is indexed by an integer $i = 1, \dots N$, consists of an origin $\mathbf{o}_i$, direction $\mathbf{d}$ (identical for all rays), and a real-valued field magnitude a_i. For a beam of waist w_0 initially centered at $\mathbf{O}$ and propagating in the direction $\mathbf{d}$, the rays' origins are chosen randomly along a length-$5w_0$ line that is centered at $\mathbf{O}$ and is orthogonal to $\mathbf{d}$. For a beam of total power P initialized in a medium with impedance Z_0, the ray magnitudes are $a_i = \sqrt{4Z_0 P/\pi w_0^2}\exp(|\mathbf{o}_i - \mathbf{O}|^2/w_0^2)$. Once initialized, rays may be traced through an arbitrary arrangement of perfectly reflective mirrors and thick biconvex lenses using the laws of reflection and refraction. To model the effects of acoustic waves on beam propagation, we further implement ray tracing [2] and optical path length computation [3] through regions of inhomogeneous refractive index. The Sagnac interferometer is modeled by launching two identical beams into the system depicted in Fig. 1. The beamsplitter is modeled by including a 45°-oriented mirror in place of the beamsplitter for one of the beams, but not the other. Beamsplitter phase shifts will be handled later. We use a pixelated detector model [4] at the cut mirror's location to compute the interference pattern emerging from the interferometer's dark port. The detector consists of pixels $k = 1, \dots, M$ uniformly spaced over a width of $6w_0$. For each traced beam $j = 1, 2$, we compute the pixel-average magnitudes $\overline{a}_{j,k}$ and optical path lengths $\overline{\ell}_{j,k}$ over all rays from beam j incident on pixel k. The pixel-averaged optical phase is then $\overline{\phi}_{j,k} = 2\pi\overline{\ell}_{j,k}/\lambda$ for a beam with wavelength λ. After two passages through the beamsplitter, the two beams at the dark port pick up an additional relative phase shift of π, as demanded by the conservation of energy [5, 6]. Without loss of generality, this relative phase shift is enforced in our simulation by sending $\overline{\phi}_{2,k} \to \overline{\phi}_{2,k} + \pi$. The pixelated interference pattern is then $I_k = \left|\overline{a}_{1,k}e^{-i\overline{\phi}_{1,k}} + \overline{a}_{2,k}e^{-i\overline{\phi}_{2,k}}\right|^2 / 2Z_0$ Finally, the signal from split beam detection of this interference pattern is modeled as proportional to $S = \sum_{k=1}^{M/2} I_k - \sum_{k=M/2+1}^{M} I_k$.

The acoustic source is modeled as a spherical wave of refractive index $n(\mathbf{r}, t)$ at coordinate point $\mathbf{r}$ and time t. For a temporal wave profile $f(t)$ with characteristic acoustic pressure p_0 at a distance r_0 from the spherical epicenter $\mathbf{c}$ in a medium with sound speed c_0 and refractive index n_0 whose pressure dependence is, to first order, $\partial n_0/\partial p = Q$, we have

$$n(\mathbf{r}, t) = n_0 + \frac{Q\, p_0\, r_0}{|\mathbf{r} - \mathbf{c}|} f\left(t - \frac{|\mathbf{r} - \mathbf{c}|}{c_0}\right). \tag{S2}$$

The refractive index gradient is

$$\nabla n(\mathbf{r}, r) = \frac{-Q\, p_0\, r_0}{c_0} \frac{\mathbf{r} - \mathbf{c}}{|\mathbf{r} - \mathbf{c}|^3} \times \left[c_0 f\left(t - \frac{|\mathbf{r} - \mathbf{c}|}{c_0}\right) \quad + |\mathbf{r} - \mathbf{c}|\dot{f}\left(t - \frac{|\mathbf{r} - \mathbf{c}|}{c_0}\right)\right]. \tag{S3}$$

In Fig. 1 (b-c), we use realistic parameters $f(t) = p_0 \sin(2\pi f_0 t)$, $p_0 = 100\,\mathrm{Pa}$, $f_0 = 40\,\mathrm{kHz}$, $r_0 = 10\,\mathrm{cm}$, $c_0 = 346\,\mathrm{m/s}$, $n_0 = 1$, and $Q = 4.86 \times 10^{-8}\,\mathrm{Pa}^{-1}$ [7]. The telescope lenses are assigned a refractive index of 1.5, thickness of 9.89 mm, and curvature radius of 148.33 mm for an effective focal length of 150.00 mm. Within the gradient index medium each ray is propagated in steps of constant $\mathrm{d}s/n(\mathbf{r}, t) = 5 \times 10^{-5}$. The interference pattern is calculated using 10 000 rays per beam, each with a waist of $w_0 = 3\,\mathrm{mm}$, and a detector with $M = 1001$ pixels.

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