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A fly-inspired directional microphone with integrated-photonic microring resonator transduction

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Abstract

Photonic integrated circuits offer compactness, wafer-scale manufacturability and a fast-maturing fabrication base. Here we report what is, to our knowledge, the first fly-inspired directional microphone transduced by integrated photonics: two silicon-nitride microring resonators on opposite wings of a rocking diaphragm, monolithically released above a backside Bosch-etched cavity. Off-axis sound drives the antisymmetric rocking mode, straining one ring in tension and the other in compression; with the laser biased on each ring's resonance slope, the opposite resonance shifts become two intensity signals of opposite phase, whose difference transduces the direction-bearing motion. The packaged device shows loaded optical quality factors of 18,635 and 17,974 near 1553 nm; scanning laser-Doppler vibrometry resolves the rocking mode near 15.8 kHz and the bending mode near 20.8 kHz. Tone-burst excitation at the two modal resonances demonstrates directional transduction directly in the time domain: at 90° incidence the two ring outputs oscillate in antiphase and their difference is enhanced, whereas at 180° they are in phase and the difference is suppressed. The optical response appears only after the acoustic time-of-flight and rings down after the drive ends, excluding electromagnetic pickup. Finite-element projections of an audio-band device, using shot-noise scaling, indicate an A-weighted signal-to-noise ratio of 74.6 dB(A), more than 10 dB beyond an optimized piezoelectric implementation of the same mechanics. These results constitute a proof-of-concept demonstration of a new transduction platform for chip-scale directional acoustic sensing, with a quantitative roadmap — higher optical quality factor, power— toward practical performance improvement.

Introduction

Capturing the direction of a sound within a millimetre-scale device is a long-standing goal in microscale sensing and a gating requirement for emerging applications ranging from smart glasses and augmented-/virtual-reality headsets to robotics, in-cabin sensing and — most consequentially — hearing aids, where understanding speech in background noise remains the most pressing unmet need and array beamforming has been the most convenient method[1]. Conventional directionality, however, is obtained from spatial apertures and microphone-array baselines whose dimensions scale with the acoustic wavelength, so that shrinking the device sacrifices directional fidelity[2]. A fundamentally different route is offered by biology.

The parasitoid fly *Ormia ochracea* localizes the calling song of its cricket host with an accuracy of a few degrees, despite an inter-ear separation of only ~ 0.5 mm — hundreds of times smaller than the acoustic wavelength[3]. This hyperacute performance arises not from the arrival-time and level differences that vertebrates exploit, but from a mechanical coupling between the two tympana that amplifies the minuscule interaural cues into a large, mechanically separable difference in membrane motion[3,4,5,6]. Direction is thereby encoded in the relative amplitudes and phases of a small set of orthogonal vibration modes of a sub-wavelength structure, a principle that maps naturally onto chip-scale micromechanics.

Fly-inspired MEMS microphones have translated this principle into silicon chips, using capacitive, comb-drive and piezoelectric transduction to reproduce direction-dependent membrane mechanics and demonstrate sound-source localization[7,8,9,10,11,12,13,14,15,16,17]. These devices confirm that a properly designed teeter-totter or coupled-membrane diaphragm converts sound-incidence angle into distinct superpositions of a symmetric (bending) mode and one or more antisymmetric (rocking) modes, most recently yielding microphones that combine an omnidirectional output with two orthogonal in-plane directivities on a single chip[17]. They also expose the central bottleneck: the direction-bearing modes generate weak, distributed strain fields, and area-integrated electrical readout couples the achievable signal-to-noise ratio (SNR) to the limited transducer footprint. Because piezoelectric voltage scales with integrated charge, high SNR forces large electrodes, which in turn forces the mechanical design toward broad, uniform strain plateaus rather than the sharply localized strain maxima that best separate the modes — shrinking the usable design space and limiting modal selectivity.

Optical readout can break this area–SNR coupling. Free-space and grating-interferometric detection of MEMS microphone diaphragms, including fly-inspired ones, has reached very low noise floors[18,19,20,21], but these approaches require bulky external optics and do not exploit on-chip waveguide confinement. Integrated photonics offer a compelling alternative: a high-quality-factor (high-Q) optical microcavity converts an extremely small mechanical perturbation into a measurable shift of its resonance, transducing strain at a localized region with cavity-enhanced sensitivity that grows with Q and is independent of the sensing footprint. Silicon-nitride and silicon-on-insulator microring resonators have accordingly enabled highly sensitive, miniaturized ultrasound and acoustic detectors[22,23,24,25,26,27,28]. What has been missing is the union of the two ideas — fly-inspired directional mechanics and integrated-photonic transduction — in a single monolithic device.

Here we close that gap. We demonstrate a directional microphone in which a fly-inspired rocking diaphragm is transduced by two silicon-nitride microring resonators, one on each wing of the central hinge. Off-axis sound drives the antisymmetric rocking mode, straining the two rings in opposition and detuning their optical resonances differentially; slope detection on each ring converts this into an intensity signal, and the difference of the two channels recovers the direction-bearing motion while rejecting the common-mode response. We characterize the device optically (loaded Q = 18,635 and 17,974 near 1553 nm), mechanically (rocking mode near 15.8 kHz and bending mode near 20.8 kHz by scanning laser-Doppler vibrometry) and acoustically, where tone bursts applied at the two modal resonances produce the two predicted signatures: antiphase ring outputs with an enhanced differential channel at 90° incidence, and in-phase outputs with a suppressed differential channel at 180° incidence. As a first demonstration of the concept, the emphasis of this work is the transduction principle itself rather than exhaustive acoustic calibration; the demonstration establishes a new, CMOS-compatible transduction platform and a quantitative roadmap — higher Q, higher optical power and improved extinction ratio — toward practical performance, which we quantify with simulations of an audio-band design projecting an A-weighted SNR of 74.6 dB(A), more than 10 dB beyond an optimized piezoelectric implementation of the same mechanics.

Results

Operating principle and device architecture

A complete description of the sound field at a point requires four scalar quantities — the acoustic pressure p_0 and the three orthogonal components of its gradient ∇p — because the linearized momentum equation identifies the pressure gradient as the quantity that distinguishes one propagation direction from another[29,30]:

$$\rho_0 \frac{\partial u}{\partial t} = -\nabla p$$

1

A conventional microphone measures only p_0 and discards ∇p. A fly-inspired diaphragm instead projects the field onto its mechanical eigenmodes: writing the diaphragm deflection as a modal superposition,

$$U(x, y, z, t) = \sum_i \psi_i(x, y, z)\, Re\left[\eta_i(\omega)\right] e^{j\omega t}$$

2

with orthogonal mode shapes ψ_i and modal coordinates η_i obeying a driven-harmonic-oscillator relation,

$$\eta_i(\omega) = \frac{F_i}{\omega_i^2 - \omega^2 + 2j\delta\omega}, \quad F_i = \int \psi_i \cdot p\, dV$$

3

the modal force F_i is the overlap of the pressure field with the *i*-th mode shape. A symmetric (bending) mode integrates the uniform part of the field and couples to p_0, whereas an antisymmetric (rocking) mode couples to the in-plane pressure gradient while rejecting p_0. Sound from different in-plane directions therefore excites different superpositions of the symmetric and antisymmetric modes, and the incidence angle is encoded in the relative modal weights.

Our device realizes this principle with two silicon-nitride microring resonators placed on opposite wings of a fly-inspired rocking diaphragm (Fig. 1). Computer renderings of the chip show the fiber-array connection to the on-chip bus waveguides and the two microrings (dual MRRs) at the diaphragm center, together with the backside Bosch-etched cavity that releases the diaphragm from the handle silicon (Fig. 1, right). The main illustration traces the full transduction chain. An off-axis acoustic wave rocks the diaphragm about its central hinge, straining MRR1 in tension while MRR2 is compressed. Each ring is an all-pass resonator interrogated by continuous-wave (CW) light at a fixed laser wavelength λ_{laser}: tension red-shifts the resonance of MRR1 while compression blue-shifts that of MRR2, so with the laser biased

on the slope of each Lorentzian notch the equal-and-opposite resonance shifts $\Delta\lambda_{res}$ are converted into equal-and-opposite changes of the transmitted intensity. The two photoreceiver outputs I_1 and I_2 therefore oscillate 180° out of phase for rocking motion, and their subtraction doubles the directional signal while rejecting common-mode intensity noise and the symmetric (bending) response.

Cavity-enhanced slope detection and Q-scaling

The transduction gain follows from the all-pass microring transfer function. Light on the bus waveguide sees a Lorentzian notch,

$$P(\omega) = P_0 - \frac{D}{1 + \left(\frac{\omega - \omega_0}{H}\right)^2}$$

4

with off-resonance power P_0, extinction D and half-width H, so that the loaded quality factor is $Q = \omega_0/2H$. Biasing the laser on the steepest part of the notch (Fig. 1) converts a small mechanically induced change of the ring optical path length ΔL into a proportional change in detected power; the maximum slope gives a displacement responsivity that scales linearly with Q,

$$\frac{dP}{dL} = \sqrt{3}\, D\, \frac{Q}{L}$$

5

where L is the ring circumference. Eq. (5) is the central advantage of photonic transduction: sensitivity is amplified by the optical Q within a fixed, localized footprint for a given strain, so — unlike area-integrated electrical readout — SNR is decoupled from the size of the sampling region. Combining the slope response with the modal strain sampled along the ring path yields a pressure responsivity

$$\frac{dP}{dp} = \sqrt{3}\, P_0\, Q\, \frac{dS_{avg}}{dp}$$

6

where S_{avg} is the average modal strain along the ring circumference. For shot-noise-limited detection at photodiode responsivity R, DC photocurrent $I_{DC} = R \cdot P_{DC}$ and bandwidth B, the input-referred minimum detectable pressure (noise-equivalent pressure, NEP) is

$$NEP = \frac{\sqrt{2qRP_{DC}}}{\sqrt{3}\, R\, P_0\, Q\, \frac{dS_{avg}}{dp}}$$

Equations (5)–(7) show that the noise floor improves with increasing optical Q, increasing optical power and increasing extinction (through D and P_0) — the three levers that define the roadmap in the Discussion.

Optical characterization

The completed chip is packaged onto a printed-circuit board with a fiber-array unit vertical-coupled to the bus waveguides and wire bonds to the two thermo-optic modulators, which allow the ring resonances to be tuned relative to the laser line to set the operating point. Optical resonances are measured with a tunable laser TLX1 from Thorlabs detected by a photodiode from Thorlabs DET01CFC and transimpedance amplifier. An optical micrograph shows the two racetrack microring resonators on the diaphragm (Fig. 2b). Lorentzian fits to the normalized notches (Fig. 2c,d) give loaded quality factors of Q = 18,635 for MRR2 (port 56) and Q = 17,974 for MRR1 (port 78), with resonances near 1553.2 nm and 1552.9 nm in the telecom C-band. These values, approaching 2×10^4, determines the transduction gain of the present device through Eqs. (5)–(7).

Mechanical characterization

Scanning laser-Doppler vibrometry (LDV) resolves the diaphragm modes and their resonant frequencies (Fig. 3a). The GDS layout identifies the thermo-optic modulators and the two microring resonators (Fig. 3b), and an optical micrograph of the packaged device shows the two thermo-optic-modulator wire bonds and the fiber-array-unit connection (Fig. 3c). The measured displacement spectrum resolves two low-order modes: the antisymmetric rocking mode (Mode 1) near 15.8 kHz and the symmetric bending mode (Mode 2) near 20.8 kHz (Fig. 3d). Full-field scans confirm the mode shapes: the rocking mode moves the two wings in opposition about the central hinge (Fig. 3e) — the motion that strains the two rings with opposite sign — while the bending mode moves them in phase (Fig. 3f). The rocking mode is therefore the direction-bearing mode transduced by the differential readout, and the two well-separated resonances provide natural test tones at which each mode can be excited selectively in the acoustic experiments below.

Fabrication

The device is fabricated with a CMOS-compatible silicon-nitride-on-silicon process (Fig. 4). Bus waveguides, microrings and thermo-optic-modulator heaters are defined in the silicon-nitride device layer on thermal oxide (a). Backside photoresist is spun and patterned (b) and a backside reactive-ion etch (RIE) defines the backside hard mask (c); topside photoresist patterning (d) and topside RIE (e) define the topside hard mask. A timed topside deep reactive-ion etch (DRIE) forms the diaphragm relief (f), and a backside DRIE removes the silicon handle to release the suspended, mechanically compliant

diaphragm of the photonics integrated circuit chip (g). The flow uses only standard foundry-compatible materials and tools, so the transducer is monolithically integrated with its mechanical structure on a single chip.

Acoustic time-domain demonstration of directional transduction

For acoustic testing the packaged chip is mounted on a 3D-printed bracket on a rotation stage and excited by a loudspeaker at a fixed standoff, so that the incidence angle θ between the sound and the diaphragm can be set while the two ring photoreceiver outputs and the loudspeaker drive voltage are recorded simultaneously (Fig. 5a,d). Rather than attempting a full acoustic calibration, we designed the experiment to expose the two signatures that uniquely identify differential photonic transduction of the fly-inspired mechanics: the relative phase of the two optical channels, and its dependence on which mechanical mode is excited. A short tone burst applied at one modal resonance excites that mode selectively, and the burst also separates, in time, the electrical drive from the acoustic response. With the device at 180° incidence and the burst at 20.8 kHz — the bending resonance — the two ring outputs respond in phase and the differential channel MRR1 − MRR2 is strongly suppressed (Fig. 5b,c): the symmetric mode strains both rings identically and is rejected by subtraction. With the device rotated to 90° and the burst at 15.75 kHz — the rocking resonance — the two ring outputs respond in antiphase and the differential channel response exceeds either individual channel (Fig. 5e,f): the antisymmetric mode detunes the rings in opposition, exactly as designed. In both cases the optical response appears only after the acoustic time-of-flight from the loudspeaker to the chip and persists as a mechanical ring-down after the electrical drive has ended (Fig. 5b,e); electromagnetic pickup would instead be synchronous with the drive voltage, so the detected signal is unambiguously acousto-mechanical in origin. Together the two measurements demonstrate, in a single time-domain picture, that incidence direction is encoded in the two on-chip optical channels and recovered by their subtraction.

Projected performance: an audio-band optical fly microphone

The demonstrated device places its rocking resonance near 15.8 kHz, above the audio band in which directional hearing aids and hearables operate. To illustrate what monolithic photonic integration enables on this platform, we have simulated an audio-band first-generation variant with much thinner diaphragm and thus lower resonance frequency, currently under fabrication, that couples a more compliant fly-inspired rocking membrane to the same differential microring readout (Fig. 6). Two microrings are placed symmetrically about the central hinge, and the integrated thermo-optic modulator provides phase tuning to compensate fabrication-induced optical mismatch and enable balanced differential readout (Fig. 6a). Under acoustic excitation the membrane rocks so that the two wings experience opposite strain (Fig. 6b), producing opposite optical-path-length perturbations in the two rings. The simulated differential optical-path-length response peaks near the rocking-mode resonance at ≈ 1.15 kHz (Fig. 6c), and the simulated angular response at 1150 Hz exhibits the dipole directivity

expected of a pressure-gradient sensor (Fig. 6d). Like the demonstrated device, this first-generation design resolves a single directional axis.

Using the scaling of Eqs. (5)–(7) with the FEM-derived pressure derivative of the average modal strain, dS_{avg}/dp — assuming a loaded optical Q of 1×10^6, a 10 dB extinction ratio and 1 mW of on-chip optical power — Fig. 6e compares the projected minimum detectable pressure (MDP — the shot-noise-limited noise-equivalent pressure of Eq. (7)) of the audio-band optical fly microphone against an optimized AlScN piezoelectric and against representative commercial omnidirectional microphones from Knowles (SPW0878LR5H-1) and Infineon (IM66D130MV01 and IM70A135V01). The optical implementation is projected to achieve the lowest MDP across the audio band, with an A-weighted self-noise of 19.4 dB(A) and an A-weighted SNR of 74.6 dB(A) — a directional-mode SNR improvement exceeding 10 dB over the best piezoelectric embodiment of the same mechanics — while simultaneously providing directional information that omnidirectional parts cannot supply on a single monolithic chip. This projection quantifies the advantages of the platform demonstrated above: the same mechanics read out piezoelectrically remain transduction-limited, whereas the cavity-enhanced photonic readout converts available optical Q, optical power and localized strain directly into a much-improved noise-floor.

Discussion

The device reported here is, to our knowledge, the first directional microphone to combine fly-inspired directional mechanics with integrated-photonic transduction. It demonstrates the full signal transduction chain end to end: a rocking diaphragm that encodes incidence angle in an antisymmetric mode, two on-chip silicon-nitride microrings that transduce the resulting differential strain, slope detection that converts resonance detuning into intensity, and channel subtraction that recovers the direction-bearing signal. The measured mode-resolved phase signatures — antiphase ring outputs with an enhanced difference at the rocking resonance for 90° incidence, and in-phase outputs with a suppressed difference at the bending resonance for 180° incidence (Fig. 5) — confirm that the direction-bearing rocking mode is transduced selectively and differentially by the photonic readout.

We emphasize what this first demonstration claims. It is a demonstration of a transduction concept, not of calibrated microphone performance: we have deliberately restricted the acoustic experiments to mode-selective, time-domain measurements that identify the transduction mechanism unambiguously, and we leave calibrated sensitivity, noise-floor and full directivity characterization — which demand controlled acoustic instrumentation and setup— to a dedicated follow-up study. Several non-idealities of the present device are likewise not fundamental: the loaded $Q \approx 1.8\times10^4$ is modest for silicon-nitride photonics; only the single rocking axis is resolved, so the device is directional in one in-plane dimension rather than fully two-dimensional; and the fiber-array package likely scatters sound in the immediate vicinity of the diaphragm. The value of the result is that it establishes directional acoustics platform based on an entirely new sensing paradigm and, through Eqs. (5)–(7), a quantitative scaling law for practical performance improvement.

The roadmap follows directly from Eqs. (5)–(7). First, optical quality factor: the responsivity scales linearly with Q and the shot-noise-limited noise-equivalent pressure as 1/Q, and silicon-nitride microrings is capable of reaching $Q \approx 1\times10^6$ — nearly two orders of magnitude above the present devices, with a proportional improvement in noise floor from Q alone. Second, optical power: shot-noise-limited performance improves as $1/\sqrt{P_{DC}}$, so raising the on-chip power (within thermal and nonlinear limits) directly lowers the noise floor. Third, extinction ratio: a deeper resonance increases the slope factor (D and the on-slope power P_0), further raising responsivity. Combining these gains with an audio-band mechanical design projects noise floors far below the present device: the simulations of Fig. 6 indicate an A-weighted SNR of 74.6 dB(A), exceeding an optimized piezoelectric embodiment of the same mechanics by more than 10 dB and entering the regime relevant to consumer and hearing-assistive applications. Beyond sensitivity, extending the architecture to four rings arranged as two differential pairs — one pair on the strain maximum of each of the two orthogonal directional modes — would resolve both in-plane pressure-gradient components and enable full two-dimensional reconstruction of incidence direction on a single monolithic chip, a capability recently demonstrated with piezoelectric transduction[17].

Chip-scale directional microphones of this kind could benefit hearing aids and hearables (where speech-in-noise is the dominant unmet need), AR/VR spatial audio, robotics and human–machine interaction, and distributed acoustic localization. More broadly, the demonstration shows that integrated photonics — with its cavity-enhanced, footprint-independent and inherently multiplexable readout — is a natural transduction layer for bio-inspired acoustic sensors, opening a design space in which the mechanical structure and the optical cavity can be co-optimized rather than compromised against each other.

Materials and methods

Device design and finite-element modelling

The diaphragm geometry, mode shapes and strain fields were computed by finite-element analysis (COMSOL Multiphysics). Eigenfrequency analysis identified the antisymmetric rocking mode and the symmetric bending mode, in agreement with the LDV-measured mode shapes and resonant frequencies (Fig. 3); the strain at the ring locations was extracted to evaluate the average modal strain S_{avg} sampled along each ring circumference. The strain fields were combined with the all-pass microring slope-detection model of Eqs. (4)–(6) to optimize the placement of the two rings on the strain extrema of the rocking mode.

Fabrication

Devices were fabricated on a silicon-nitride photonics integrated circuit platform (Fig. 4). Bus waveguides, microring resonators and thermo-optic-modulator heaters were defined in the silicon-nitride device layer on thermal SiO_2. Backside and topside photoresist layers were patterned and transferred into hard masks by reactive-ion etching; a timed topside deep reactive-ion etch (DRIE) defined the

diaphragm relief, and a backside DRIE through the silicon handle released the suspended diaphragm carrying the photonic devices. Metal layers provided the thermo-optic heaters and bond pads.

Optical characterization

Optical resonances were measured with a tunable laser from Thorlabs TLX1 by sweeping the wavelength controlled by computer; at each set point the laser was held briefly and the transmission was read as the average of the last few seconds after it stabilized (Fig. 2a). The output from each was detected by a photodiode followed by a transimpedance amplifier. Loaded quality factors were obtained by fitting the normalized notch of Eq. (4) with a Lorentzian lineshape, giving $Q = \omega_0/2H$.

Mechanical characterization

Diaphragm mode shapes and resonant frequencies were measured with a scanning laser-Doppler vibrometer (Polytec PSV-500). Full-field scans resolved the rocking and bending mode shapes, and the displacement spectrum determined the resonant frequencies (rocking mode near 15.8 kHz; bending mode near 20.8 kHz).

Acoustic measurement

Acoustic excitation was provided by a loudspeaker placed at a fixed standoff from the device. The packaged chip was mounted on a 3D-printed bracket on a rotation stage, allowing the in-plane incidence angle θ to be set to 90° or 180°. Short sinusoidal tone bursts at 15.75 kHz (rocking resonance, 90°) and 20.8 kHz (bending resonance, 180°) were applied to the loudspeaker, and the two microring photoreceiver outputs were recorded simultaneously with the loudspeaker drive voltage with the same trigger; for the time-domain traces (Fig. 5) the channel means were removed and the differential channel MRR1 − MRR2 was formed offline. The delay between the electrical drive burst and the arrival of the optical response, set by the acoustic time-of-flight from loudspeaker to chip, together with the mechanical ring-down after the drive ended, was used to rule out electromagnetic pickup as the origin of the detected signals.

Performance projections

The audio-band design of Fig. 6 was modelled by finite-element analysis (COMSOL Multiphysics): eigenfrequency analysis identified the rocking mode and its antisymmetric strain field, and the differential optical-path-length response $\Delta L(f)$ and its angular dependence $\Delta L(\theta)$ were computed from the modal strain sampled along the two ring paths. Projected MDP spectra (Fig. 6e) were obtained from the slope-detection model of Eqs. (4)–(7) with the FEM-derived dS_{avg}/dp, assuming shot-noise-limited detection with a loaded optical Q of 1×10^6, a 10 dB extinction ratio and 1 mW of on-chip optical power, and compared with an optimized AlScN piezoelectric implementation and with representative commercial omnidirectional microphones (Knowles SPW0878LR5H-1, bottom-port differential analog, 65 dB(A) SNR; Infineon IM66D130MV01, digital, 66 dB(A) SNR; Infineon IM70A135V01, analog, 70 dB(A) SNR); A-weighting over the audio band yields the quoted self-noise and SNR figures.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Code availability

The finite-element and data-analysis code used in this study is available from the corresponding author upon reasonable request.

Declarations

Competing interests

The authors declare no competing interests.

Author contributions

Q.H., Y.M. and N.A.H. conceived the idea. Y.M. and Q.H. designed the photomask, fabricated and packaged the devices, and designed and conducted the optical, mechanical and acoustic experiments. Q.H. prepared the figures. E.V. assisted with the COMSOL finite-element simulations. E.V., Z.L. and W.W. contributed to manuscript preparation and to scientific discussion of the experimental details. Y.M. and Q.H. analysed the data and wrote the manuscript. N.A.H. supervised the project and edited the manuscript. All authors discussed the results and approved the final manuscript.

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