PHOTOACOUSTICS

Acoustic sensing with light

Optical acoustic sensors have gained interest for use in photoacoustic imaging systems, but can they dethrone conventional piezoelectric sensors altogether?

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Photoacoustic tomography (PAT) is a hybrid biomedical imaging modality that provides the molecular contrast of light at depths enabled by acoustic sensing. As PAT pushes the frontier to deeper and higher-resolution imaging, there is a growing demand for a new generation of sensitive and scalable broadband acoustic sensors. Optical acoustic sensors have been considered for decades[1] owing to their broad bandwidths and nearly area-independent sensitivity. Despite these desirable traits, they have not yet superceded conventional piezoelectric transducers in PAT due to practical challenges such as scalability, integration, availability and unclear sensitivity advantages in typical use-cases.

Writing in *Nature Photonics*, Wouter Westerveld and co-authors demonstrate an acoustic sensor[2] that overcomes many of these limitations. Their acoustically point-like (15–20 μm) sensor employs an optomechanical waveguide to enable high sensitivity and bandwidth. Benefitting from existing semiconductor infrastructure, the sensor is conveniently compatible with complementary metal–oxide semiconductor (CMOS) processing where fine pitch arrays with parallel readout were demonstrated. With these milestones, optical acoustic sensors are expected to become more widely adopted in PAT. Nevertheless, practitioners should consider the sensitivity advantages over piezoelectric transducers for a given application.

Piezoelectric transducers remain the most used acoustic sensors in PAT systems. While PAT involves only acoustic sensing, piezoelectric transducers are reciprocal devices capable of transmission, which is required when concurrent ultrasonography is desired. Combined with inherent mechanical and electrical losses, transducer sensitivity can be shown to degrade proportionally to the square root of sensing area[3], limiting the use of very small sensors. Conversely, optical acoustic sensors are receive-only devices and can achieve nearly area-independent sensitivity in sensor dimensions comparable with optical wavelengths.

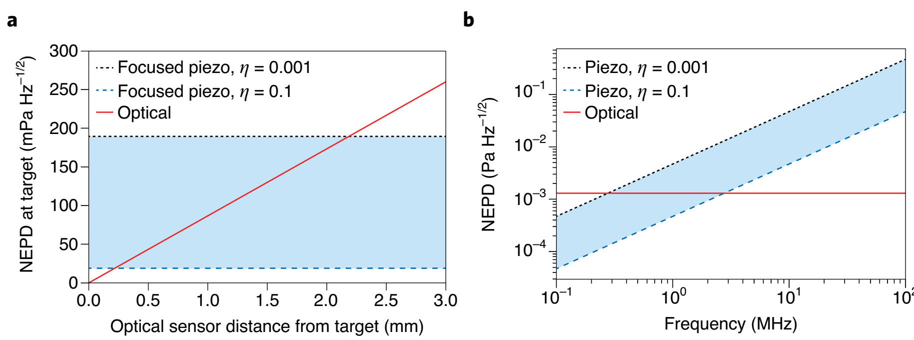

Fig. 1 | Comparison of NEPD between an example optical sensor and typical piezoelectric transducers in the two variants of PAT. a, PAM: NEPD at the target region for a point-like optical sensor at varying distance and focused piezoelectric tranducers. **b**, PACT: NEPD at the surface of point-like optical and piezoelectric detectors with dimension $\lambda/2\times\lambda/2$ at varying upper cut-off frequencies.

In optical acoustic sensors, acoustic displacement modulates the optical path length in the interaction region of a device by altering either its geometric length or refractive index[4]. Changes in the optical path length can be sensed using interferometry with respect to a reference arm (for example, Michelson or Mach–Zehnder[1]), or by detecting changes in the optical transmission through a resonant structure (for example, microring[5] or membrane resonators[6]) at a given optical wavelength. High optical quality factor on the order of 10,000 and coherent light sources are generally needed to sense acoustic displacements that are much smaller than the optical wavelength[1]. For instance, a representative incident pressure of 10 Pa at 10 MHz leads to only 100 fm of acoustic displacement in water. The device by Westerveld et al. employs an optomechanical waveguide ring resonator with a tiny 15-nm air gap, whereby slight displacement in the top membrane induces refractive index changes that alter the resonant wavelength[2]. Using light at the flank of resonance, incident acoustic signals thereby translate to optical intensity modulation detectable with high sensitivity and bandwidth.

Despite their advantages, optical sensors have not yet been widely adopted in PAT systems. One challenge is multiplexing sensor arrays, where manufacturing tolerances can lead to different optical properties in the interaction region[7], and dedicated lasers and optical detectors are often impractical. Westerveld and colleagues address this issue by fabricating arrays of slightly different sized optical resonators, allowing parallel optical readout of several sensors on a single fibre using wavelength-division multiplexing. Prohibitive costs, set-up time, and stability have also generally restricted optical sensors to the laboratories of their developers. The developments by Westerveld et al. provide a step towards more widespread adoption of optical acoustic sensors aided by the scalability of CMOS processing. On-chip laser integration remains an ongoing challenge in silicon photonics more broadly[8], but if solved would further improve the scalability of such sensors.

When evaluating sensors, one key metric for characterizing acoustic sensitivity is the noise-equivalent pressure density (NEPD), defined in amplitude spectral density (Pa Hz$^{-1/2}$). For a given bandwidth, NEPD can be converted to noise-equivalent pressure (NEP) (Pa). NEP calibrates the system noise into an effective pressure incident on the sensor surface that can be compared with incident photoacoustic signal pressure.

NEPD therefore provides a convenient benchmark of noise-limited detection across sensor architectures.

Acoustic thermal noise of the medium presents a baseline noise in all sensor types. In piezoelectric sensors, additional contributions come from thermal noise in the transducer and amplifier noise. The resulting NEPD can be found for broadband transducers as[3]:

$$\mathrm{NEPD} = \sqrt{kTZ_a F_n / A\eta} \qquad (1)$$

where k is Boltzmann's constant, T is absolute temperature, Z_a is the acoustic impedance of the medium, F_n is the noise figure of the amplifier, A is the active area of the transducer, and η is defined as the ratio of generated electric power to incident acoustic power.

In optical sensors, additional contributions consist of displacement and sensing noise. Displacement (or acousto-mechanical) noise causes fluctuations in the acoustic interaction region. If mechanical losses are exhibited in the interaction region, displacement noise is inherently generated according to the fluctuation–dissipation theorem. Sensing noise, limiting the detection of displacement, includes laser amplitude noise, shot noise and optical readout noise. Westerveld et al.'s recent benchmark in sensitivity (1.3 mPa $\mathrm{Hz}^{-1/2}$) is dominated by displacement noise in 20 μm devices, where a comparably sized piezoelectric sensor would have two orders of magnitude higher NEPD[2].

While optical acoustic sensors have far greater sensitivity than piezoelectrics per unit active area, the advantage of miniaturization should be considered from an acoustic perspective in the two variants of PAT: microscopy (PAM) and computed tomography (PACT). In PAM, larger focused piezoelectric transducers detect acoustic responses within a tight focus inside biological tissues. As an example, a transducer[3] with numerical aperture NA = 0.5; A = 30 mm^2; T = 300 K; Z_a = 1.5 MRayl; F_n = 2; η = 0.001–0.1 can achieve NEPD of 0.06–0.6 mPa $\mathrm{Hz}^{-1/2}$. Note that η is typically cited between 0.001 and 0.01 in broadband transducers[3], but values in excess of 0.1 have been reported even for fractional bandwidth of >50%[9]. As a virtual point detector with a focal radius of 0.7λ inside the tissue, where λ is the acoustic wavelength, NEPD scales up to 18–180 mPa $\mathrm{Hz}^{-1/2}$ at 100 MHz, which is far greater than that of Westerveld et al.'s optical sensor. Therefore, if invasively embedded in the focal region of interest inside the tissue, the optical sensor would achieve far greater sensitivity. A point-like sensor's effective NEPD at distance r from the point of interest scales with r/λ. Thus, at approximately 0.2–2 mm, the optical NEPD becomes greater than the focused piezoelectric transducer's (Fig. 1a). Focused optical sensors could therefore be promising in PAM using either lenses or reflectors, but have not yet been demonstrated.

In PACT, arrays of tens to thousands of sensors typically surround the object and record acoustic responses in parallel. Image reconstruction over some field of view (FOV) is subject to the spatial Nyquist sampling criterion, whereby optimal sensor spacing and size are equivalent to a half-wavelength on the tissue surface. Sensors can be either positioned directly on the FOV boundary or extended by some distance with scaled sensor dimensions. While piezoelectric NEPD relates to the sensor area as in equation (1), spherical acoustic waves from an object have pressure p which relates to distance r as $p \propto r^{-1}$. If the sensor area A scales with r^2, these two effects cancel and NEPD remains fixed at the value of half-wavelength sensors on the FOV boundary. Since further size and spacing reduction provides no appreciable benefit in spatial sampling[10] or element directivity, we suggest that half-wavelength sized piezoelectric transducers provide a point of comparison unless the application is inherently space-constrained (for example, in near-field[7] or endoscopic[11] imaging).

As a simple comparison of PACT sensitivity, we again consider Westerveld et al.'s optical sensor NEPD benchmark of 1.3 mPa $\mathrm{Hz}^{-1/2}$ approximated as uniform across frequency[2]. While different optical sensor architectures may exhibit non-uniform NEPD, Westerveld et al.'s is one of the lowest reported regardless of size or frequency. This sensor is compared with conventional piezoelectric sensors according to equation (1), using typical values of T = 300 K; Z_a = 1.5 MRayl; F_n = 2; η = 0.001–0.1. Square piezoelectric sensor dimensions are fixed to a half-wavelength at a given upper cut-off frequency. It is evident in Fig. 1b that above ~2.5 MHz, optical sensors generally outperform piezoelectrics in PACT sensitivity. However, piezoelectric transducers may remain appealing for lower frequencies used in human-scale imaging, where the current complexity of optical sensors may not be justified.

Westerveld et al.'s optical acoustic sensor presents a new benchmark in sensor size, sensitivity and integration. Nevertheless, when considering optical sensors for use in PACT, we suggest comparing against half-wavelength-sized piezoelectric sensors since there is no acoustic benefit to them being smaller. Optical sensors have a clear benefit at higher frequencies and in space-constrained applications, but piezoelectric transducers may remain advantageous in lower frequency applications such as human-scale imaging. Similarly, unless optical sensors can be placed directly in the imaging region, microscopy imaging is likely to continue to benefit from larger focused piezoelectric transducers. Nevertheless, optical acoustic sensors like Westerveld et al.'s present great promise in advancing PAT to deeper and higher-resolution imaging, and in opening new applications as performance and integration continue to improve. ❒

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Competing interests

L.W. has a financial interest in Microphotoacoustics, Inc., CalPACT, LLC, and Union Photoacoustic Technologies, Ltd., which, however, did not support this work.