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Solar desalination

## Optomechanical chaos

**JUNE 2016** VOL 10 ISSUE 6

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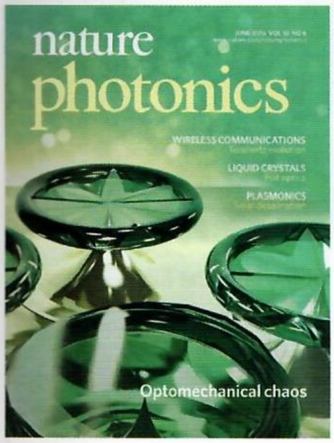

### COVER IMAGE

**An optomechanical microresonator formed from a glass microtoroid (pictured) is shown to support the transfer of optical chaos from a strong pump signal to a weaker probe signal via mechanical motion of the resonator.**
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IMAGE: F. MONIFI, S. K. ÖZDEMIR, B. PENG AND L. YANG

COVER DESIGN: BETHANY VUKOMANOVIC

### ON THE COVER

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# Optical microphone hears ultrasound

Balthasar Fischer

An Austrian start-up describes how its membrane-free optical microphone technology is being put to good use in ultrasonic non-destructive testing and process control.

Acoustics is a world of small quantities. The movement of a human eardrum during an everyday office conversation is on the order of 0.1 μm (ref. 1). Impressively, state-of-the-art microelectromechanical systems technology means that even a US$ 1 mobile phone microphone can now resolve a membrane movement on the scale of 1/500th of the diameter of a hydrogen atom. Hence, one faces demanding technical specifications when attempting to measure sound by optical means. A common approach is to optically detect the acoustically induced mechanical movement of a cantilever or a reflective membrane[2]. The idea, which is associated with spy movies from the communist era where an agent would tap into a conversation in another room by detecting the movement of the window through the deflection of a light beam[3], was in fact accomplished much earlier. As early as 1880, the famous British inventor Alexander Graham Bell used the deviation of a reflective membrane illuminated by sunlight to transduce speech into an electrical signal. Bell considered his so-called photophone to be the most important invention of his lifetime[4].

However, microphones based on moving mechanical parts such as membranes — whether in electrical or optical devices — have limitations because they are influenced by the mechanical properties of the structures involved that behave as a coupled spring–mass system. For example, a microphone containing a membrane or a mechanically deformable piezoelectric material has several distinct resonance frequencies. Damping the system makes it possible to improve the linearity of the device's frequency response, but at the cost of a reduction in sensitivity.

XARION Laser Acoustics, an Austrian-based start-up company, founded in 2012 as a spin-off from Vienna University of Technology, is developing a new family of acoustic sensors in which the acoustic pressure wave is detected purely optically by a miniature Fabry–Pérot etalon. This etalon is a small interferometric cavity formed by two parallel millimetre-sized semi-transparent mirrors (Fig. 1). The novelty of the sensor lies in the fact that it does not operate by sensing motion or deformation of its cavity mirrors, as one might expect. Instead, it works by sensing a tiny change in the refractive index of the sound-propagating medium within the cavity itself. A 1-mW beam, emitted from a 1,550-nm laser diode, operated in continuous-wave mode, is sent via an optical fibre to the Fabry–Pérot etalon. The moment the pressure inside the cavity changes, the intensity of the transmitted (and also reflected) light intensity is modulated accordingly. Because a simple sensor set-up using a single fibre is preferred for many applications, the reflected light is monitored. The beams travelling to and coming from the sensor head within a common optical fibre are split using an optical circulator, so that the reflected light from the sensor can be monitored.

The laser emission wavelength is stabilized to the optical cavity by the use of an electrical feedback current. This stabilization is important to avoid changes in the strength of the signal due to a small shift in wavelength that could be mistaken for a refractive index change within the cavity. Furthermore, ambient temperature or static pressure changes can be compensated, as they typically happen on a much slower timescale compared with acoustical events. Fortunately, because in acoustics, one is only interested in the alternating component of the pressure and not the static pressure, a slow control circuit can be used. Slowly

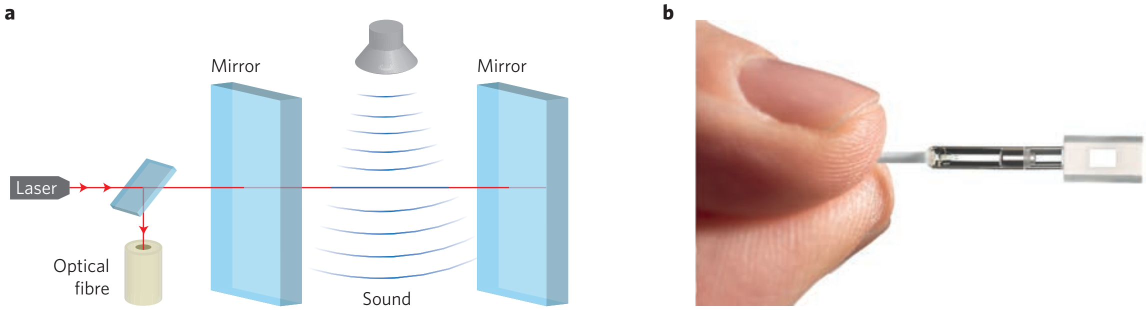

**Figure 1 |** The membrane-free optical microphone. **a**, Schematic and principle of operation of the device, whereby a sonic or ultrasonic signal is detected optically via the modification of the refractive index of a medium within a Fabry–Pérot etalon. **b**, A manufactured sensor shown with a connection to an optical fibre. Panel **b** courtesy of Leonhardt Bauer, XARION.

varying quantities such as temperature, environmental pressure or even laser drift are taken out of the equation. With the help of a balanced read-out, quantum shot-noise level can be achieved. The shot-noise current is approximately 1 nA in a 20-kHz bandwidth, and, although low, poses a fundamental limitation for this type of acousto-optical transducer.

The refractive index change to be resolved is very small: under standard conditions (room temperature, ambient pressure), the air's refractive index changes by about $3 \times 10^{-9}$ if pressure changes by 1 Pa (ref. 5). However, an alternating pressure of 1 Pa ($\sim 1 \times 10^{-5}$ of the ambient pressure) is rather loud already from an acoustic point of view; it roughly corresponds to the level of someone yelling in your ear from a close distance of a few centimetres. Hence, a high-performance microphone needs to resolve much lower pressures than 1 Pa. In fact, a membrane-free optical microphone can achieve an impressive pressure-resolution capacity. Refractive index changes below $10^{-14}$ can be detected[6]. This corresponds to pressure changes as small as 1 μPa (normalized to a 1-Hz bandwidth). A state-of-the art acoustic metrology capacitive microphone with a comparable sensitivity would be a 1/8-inch-diameter membrane, since the sensitivity of a 'conventional' acoustic microphone scales with size.

While a membrane-free optical microphone is not limited by these size restrictions, its true benefits lie elsewhere. Because its mirrors are so small and rigid, their mechanical resonances have no measurable influence. Hence, a microphone based on this principle can have a very flat frequency response from the infrasound (starting at about 5 Hz, where laser drift begins to dominate) up to ultrasound frequencies of 1 MHz. This upper bound of this frequency response is actually set by the medium itself as the absorption of air damps the propagation of the sound very strongly. In fact, the attenuation of an acoustic 1-MHz signal in air is on the order of 160 dB $m^{-1}$ (ref. 7).

Interestingly, the transducer is able to operate not only with air but also with liquids. It might be assumed that liquids are not compressible to a first approximation, but the refractive index of water is higher than that of air (if compared with vacuum) by a factor of more than 1,000 and this helps compensate for the loss of sensitivity. If used in water or another liquid, the transducer is operable up to frequencies of 50 MHz, with the limit being set by the fact that the sound wave approaches the dimension of the laser beam diameter[8]. At this point, the acoustic wavelength gets so short that there is a pressure maximum and a minimum inside the laser beam at the same time and the transducer will not generate an output signal.

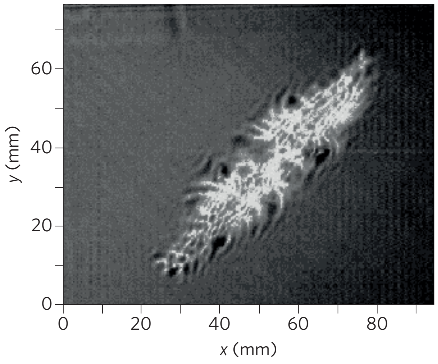

**Figure 2 |** Ultrasound scan of a carbon fibre composite plate that has internal defects, obtained with the optical sensor. Reproduced with permission from ref. 16.

Another interesting feature is the impulse response of an optical microphone, as an inertia-free transducer is better able to image a Dirac impulse (a very sharp temporal spike). This is of special interest for ultrasound detection, as conventional piezoelectric transducers are often designed to be highly resonant to achieve the desired sensitivity. This leads not only to a narrow bandwidth but also to a resonance-induced ringing, where a short acoustic pulse leads to a prolongation of the impulse by a factor of 50 or more[9].

As a result, the membrane-free optical microphone technology is particularly attractive for applications in the field of ultrasound metrology such as non-destructive testing. Methods to ascertain the mechanical integrity of components without inducing damage have been crucial in various industries for many years. For purposes such as comprehensive quality control during manufacture or in-service defect assessment and monitoring, it is not appropriate to sacrifice test objects in the process. Such inspections are particularly critical for the naval, aerospace and automotive industries as well as in construction, where material failures can compromise human safety[10].

In all these industries, the desire for robust and lightweight construction has led to the adoption of fibre-reinforced composite materials, especially carbon fibre composites in recent years. Compared with metals, they usually feature a complex, layered structure with anisotropic material properties[11] and a variety of possible defect types that need to be reliably identified[12]. Consequently, the development of non-destructive-testing techniques suitable for these materials, preferably allowing a high degree of automation to save costs as well as to increase testing speed, is of great importance[13].

One approach to defect detection is ultrasound measurements using sensitive, highly resonant, focused piezoelectric ultrasound transducers. However, as mentioned above, highly resonant transducers oscillate for many periods during pulse detection, leading to a significantly increased 'dead zone'. This term denotes the near-surface region of the test object where defect detection is rendered impossible due to overlap between the primary pulse, reflections from the sample surface and the actual signal contributed by backscattering from defects. XARION is currently working on using its optical microphone technology to perform one-sided non-destructive testing (Fig. 2), with the benefit of a resonance-free response and much reduced dead zone.

Another interesting application for ultrasound techniques is that of industrial process control. Although many industrial processes, such as chipping and machining, generate a lot of audible noise, they also generate an ultrasound spectrum that is rich in useful information. This may be a fast rotating drill that generates specific acoustic frequencies and corresponding overtones, or, to give another example, the acoustic emission of a thermal evaporation process. Further examples can be found in laser welding where high ultrasound frequencies up to the MHz range are emitted.

In the latter case, the amplitude of specific spectral components in the several hundred kHz range strongly corresponds to the penetration depth of the laser weld[14], a parameter of great relevance to the industry but that is very hard to measure. Optical monitoring systems using cameras are common, but often require sophisticated data processing to extract valuable information. The data stream of a microphone is more manageable and the analysis is comparatively easy, at least for some applications.

Acoustic process monitoring is not new, but ambient noise (something that will most probably always be present in an industrial environment) can greatly impair the predictive performance of an acoustic monitoring system. Moving to the high ultrasound regime — 300 to 900 kHz — can make this monitoring statistically much more robust simply because ambient noise is greatly reduced at these frequencies. Additionally, the attenuation by air at these high frequencies prevents interference with

**Figure 3 |** Acoustic emission monitoring at CERN, where the robustness of different materials against proton-induced damage is being investigated. Figure courtesy of Daniel Deboy, XARION.

the set-up from noise sources throughout the production facility.

While it is not likely that the membrane-free optical microphone will be particularly useful in a music recording studio, there are some instances where it could strongly aid traditional acoustic metrology. Because the sensor is coupled to a 1,550-nm single-mode optical fibre, the all-optical sensor head is immune to strong electromagnetic interference. This is not the case for capacitive acoustic sensors or piezoelectric transducers, because their commonly weak output signal (usually a few millivolts) tends to pick up disturbances along the electrical cable in a harsh environment. For example, XARION's sensors have been used by an Austrian power company to measure corona noise emitted from high-voltage power lines: the optical sensors were mounted at a distance of just 30 cm from electrical cables carrying 380,000 V.

Another demanding experimental environment where optical transducers have been deployed is for acoustic monitoring at CERN's Super Proton Synchrotron, the accelerator to the Large Hadron Collider. Here, two sensors have been installed in the accelerator tunnel to study proton impact damage to the jaw materials of the particle collimator (Fig. 3). Owing to the extreme speed of the protons in the Large Hadron Collider, which is very close to the speed of light, their energy currently reaches 6.5 TeV (~1 μJ), and because many proton bunches travel in the accelerator ring simultaneously, the total energy amounts to more than 100 MJ. It is evident that the unwanted collision of protons with the tunnel pipe aperture could lead to major damage. The collimation system protects the tunnel pipe aperture by collimator jaws with small gap sizes. Under controlled conditions, various pieces of different metal alloys are purposely bombarded with proton bunches in a dedicated materials test to assess their robustness. The sound pressure level emitted by the target container into the surrounding tunnel air can be correlated to impact damage and is a useful diagnostic tool. The Bremsstrahlung-induced radiation of the accelerated protons leads to a harsh environment, compromising the functionality of a conventional sensor. Placing the optical sensor heads close to the location of impact and using a 160-m-long optical fibre connection to a remotely located laser and detection unit makes measurements possible[15].

In summary, membrane-free optical microphone technology is now demonstrating its utility in several diverse applications. The combination of a broad frequency range of operation, a high sensitivity and a millimetre-sized sensor dimension makes the technology an interesting alternative to conventional transducers for acoustic metrology in air and liquids. ❐

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## Competing financial interests

The author is founder of XARION Laser Acoustics GmbH, which commercializes the technology discussed here.