Listening to Ultrasound with a Laser

A new way to measure ultrasound waves by optical means

Stefan Preißer, Balthasar Fischer and Nils Panzer

Fig. 1 Optical microphone for ultrasound, consisting of a rigid Fabry-Pérot etalon and an optical fiber with collimation unit.

Ultrasound is widely used in applications ranging from non-destructive testing of materials to medical imaging or even surgical interventions. As diverse as these applications may seem, they have a common interest: a precise measurement of the ultrasonic signals. Exact quantification is necessary to ensure proper performance of equipment as well as, sometimes, human safety. A new highly sensitive and broadband ultrasound detector is presented to fulfill the diverging demands of various ultrasound applications. In contrast to conventional sensors, it listens to ultrasound with a laser.

Company

XARION Laser Acoustics
Vienna, Austria

XARION Laser Acoustics GmbH is a young high-tech company, which develops and markets a novel laser-acoustic sensor. The advantages of the transducer refraining from any mechanically moving parts include a linear frequency response and a broad ultrasound frequency detection bandwidth in both air (1 MHz) and liquids (20 MHz). The company is based in Vienna and employs twenty people. The key markets comprise acoustic metrology, industrial process control, non-destructive material testing and medical imaging.

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In medical technology, ultrasound has achieved a superior standing in diagnostics and therapeutic treatments. Ultrasound is able to penetrate tissue deeply without any harm and thereby constitutes a safe, easy to apply diagnostic method. Medical sonography has proven functionality to diagnose the cause of acute abdomen, or to inspect inner organs. By using the Doppler effect, the imaging of blood velocities has been realized as well. Apart from its use in medical imaging, ultrasound is also used for therapeutic procedures such as high-intensity focused ultrasound (HIFU) or lithotripsy. To ensure high imaging quality or optimal therapeutic benefit and to prevent tissue damage by thermal effects or cavitation, the exact adjustment of the emitted ultrasound field is crucial. Hence, the sound fields of the therapeutic or diagnostic sonographic devices need to be thoroughly characterized.

In addition to classical sonography, photoacoustic imaging (PAI) is an upcoming imaging modality. Unlike in traditional sonography, where the tissue is acoustically excited by piezoelectric emitters, in PAI, the tissue is optically excited by a short laser pulse. A portion of this light is absorbed by specific absorbers inside the tissue and converted to heat, causing localized thermo-elastic pressure transients which can be detected by an ultrasonic receiver. By interpreting these pressure transients, PAI delivers additional information not accessible to conventional ultrasound imaging.

State-of-the-art ultrasound detectors rely on mechanical elements

The most commonly used detectors for ultrasound pressure waves are piezoelectric transducers, which are readily available for a range of frequency bandwidths and sensitivities. However, piezoelectric transducers have characteristics governed by the mechanical deformation of a piezoelectric material.

An important restrictive characteristic is an inherent tradeoff between sensitivity and bandwidth. Small piezoelectric transducers will be of limited sensitivity, and consequently have a limited signal-to-noise ratio. To improve the sensitivity using a given piezo material, the dimension of the active piezoelectric element has to be increased. However, increasing the transducers's diameter can cause problems in practice. First, the surface shape has to match the acoustic wave front. These so-called focused transducers are employed for several applications. This approach leads to a smaller field of view and a fixed focusing depth, beyond which the detected signal amplitude degrades. Secondly, a large transducer prohibits any endoscopic or laparoscopic use or the use in multi-element arrays.

The most prominent examples for thin layer hydrophones are polyvinylidene fluoride-based (PVDF) devices, which use very thin and flexible films to achieve a wide bandwidth. With a small influence on the measured sound-field, PVDF needle hydrophones have become the "gold-standard" in sound-field characterization [1]. A drawback of PVDF sensors is their fragile construction due to the mechanical instability of the inherently thin sensing element. This limits their use in challenging environmental conditions as well as for sensitive measurements in applications where high pressure transients can occur. Different design approaches have contributed to minimize sensor damage; however, annual re-calibration is still recommended by the IEC hydrophone measurement standards.

The large application spectrum for ultrasound detection outlined above leads to diverging requirements for modern ultrasound sensors. The ideal device would be able to detect ultrasound waves with high sensitivity and large frequency bandwidth, would have a vast dynamic range, a small footprint, and would feature good mechanical stability while being easy to calibrate and compatible to array configurations. For application in PAI and combination with optical imaging methods, the sensor should also be optically transparent.

As an alternative to piezoelectric transducers, an optical microphone (Fig.1) can listen to ultrasound by measuring the pressure-induced refractive index change of a medium, which is directly proportional to the change of density caused by an incident ultrasound wave.

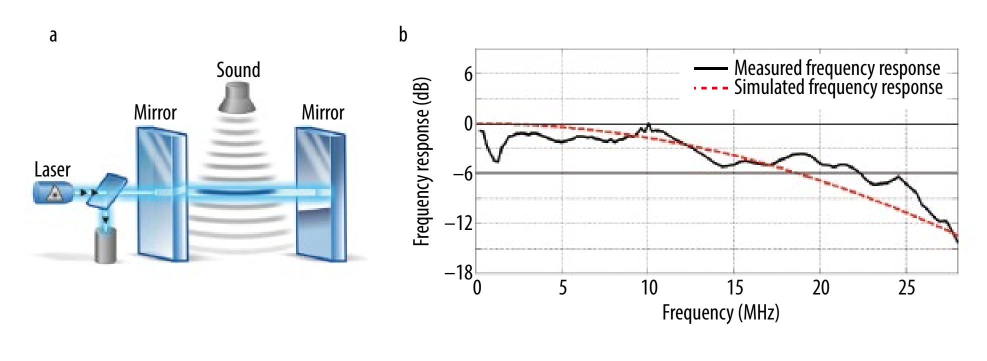

Fig. 2 Principle of operation of the optical sensor. The ultrasonic signal is detected optically by the change of the refractive index within a Fabry-Pérot etalon (a). Measured frequency response of the all-optical rigid sensor plotted as a solid black line and the simulated frequency response plotted as a dashed red line (b).

Detection principle of the optical microphone

In order to detect these density changes, the optical sensor is based on a rigid, fiber-coupled Fabry-Pérot etalon, as shown in Fig. 2a. The etalon, a miniaturized laser interferometer, consists of two non-movable semi-transparent mirrors. In the case that a specific laser wavelength is incident, constructive interference occurs inside the etalon and a high proportion of the laser light is transmitted through the etalon. When an ultrasound signal travels through the etalon, the associated change of the density of the medium between the mirrors induces a change in its refractive index. This in turn alters the wavelength of the laser, which, by consequence, does not match the fixed mirror distance anymore. This leads to an increased ratio of the reflected light, which can be precisely measured with a photodiode.

This sensing principle allows the inherently linear, resonance-free detection over a bandwidth from very low 10 Hz up to more than 20 MHz in fluids. The etalon is filled with liquid to ensure good acoustic coupling. Consisting only of non-moveable glass parts, the sensor head withstands electromagnetic interference and does not need additional calibration. Since the sensitivity of the device is determined by the optical properties of the etalon mirrors rather than the geometric size of the sensor, it combines high sensitivity with a small footprint [2]. Low noise equivalent pressure values of 1 Pa within a 20 MHz bandwidth have been demonstrated. The sensor head used in these tests has a transparent window of 2 mm × 2 mm and a broad frequency response,

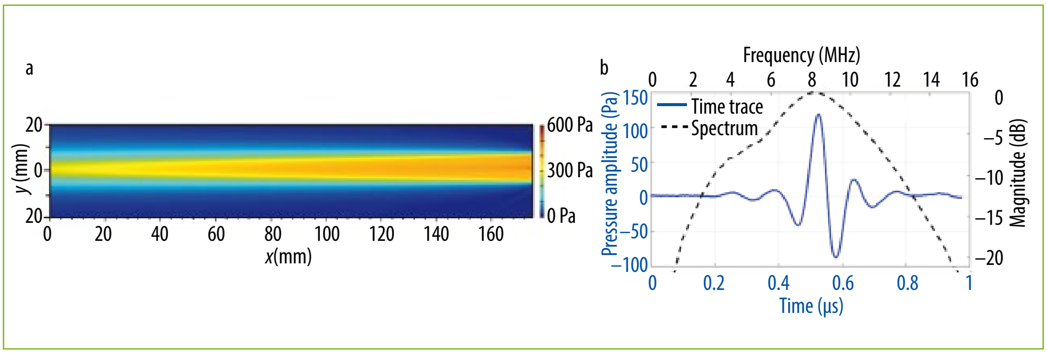

Fig. 3 Measured pressure field of a 10 MHz Panametrics V311 piezoelectric transducers (a). Pressure amplitude in far field and corresponding amplitude spectrum (b).

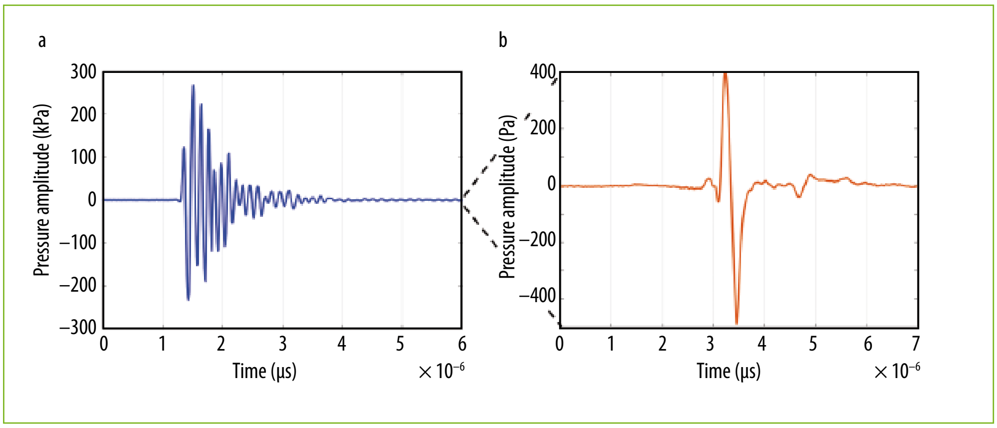

Fig. 4 Time trace measured by optical hydrophone, showing the pressure amplitude of a Doppler signal in the kPa amplitude range emitted by a linear array transducer (a). Typical photoacoustic pressure pulse in the single Pascals amplitude range (b).

shown in Fig. 2b. The highest detectable pressure amounts to 1 MPa.

Optical sensor to map sound field

The optical sensor has been successfully used to map the ultrasound field of commercially available piezoelectric transducers. The sensor's extremely small active sensing area (0.01 mm^2 for a laser beam with a diameter of 50 µm) allows for acoustic field scans of high spatial resolution as demonstrated for a 10 MHz piezoelectric transducer in Fig. 3a. In this setup, the optical sensor was scanned in a water bassin over an area of 40 mm by 176 mm. The high dynamic range of the optical hydrophone, as shown in Fig. 3a, enables the assessment of high peak pressure amplitudes, while weaker off-center signals can be still clearly resolved. In Fig. 3b, the time trace of a 10 MHz transducer measured in the far field is shown in blue, overlaid by the emitter's amplitude spectrum.

Fig. 4a shows a Doppler signal, measured with the optical hydrophone with high temporal resolution. As may become clear by comparing the scales in Fig. 4a and b, the optical hydrophone is capable to measure amplitudes both in the range of several hundred thousands of Pascals, for example, in sound field characterization, and single Pascals, in PAI.

This dynamic range combined with the small footprint of the optical detector allows to characterize transducer arrays in the near field. Due to the design of linear ultrasonic probes consisting of an array with up to 256 single elements, the acoustic far field delivers limited information about the functionality of single elements. Information of the emitted near field can be measured by scanning each piezo element separately, delivering reliable information to compare and test ultrasonic probes with a simple test design.

Photoacoustic imaging

Photoacoustic imaging is an upcoming medical imaging technique, promising to supplement valuable information to existing systems. Diverse configurations allow to image cells to organs, from microscopic to macroscopic scales. Depending on the implementation, either the excitation laser or the acoustic detector is focused on the area of interest (microscopy) [3] or a multiple element acoustic detector is used for 2D or 3D image reconstruction (tomography). Furthermore, functional imaging, such as measuring the oxygenation of blood, is possible, exploiting the fact that oxygenated hemoglobin has a different optical absorption spectrum than deoxygenated hemoglobin and can be addressed by using a different laser wavelength for excitation. By today, this method is well-studied and was confirmed in several preclinical and clinical studies [4].

In photoacoustic microscopy (PAM), pressure amplitudes in the magnitude of single Pascal need to be resolved, which is normally realized using highly sensitive large-area piezoelectric transducers. However, the use of these transducers can be challenging in reflection-mode PAM, where both the optical objective and the transducer are placed on top of the sample. While reflection-mode PAM is not limited to thin samples, still a physical contact of the transducer with the sample for acoustic coupling is needed. Since the opaque transducer cannot be placed easily in the optical path of the highly focused excitation laser, it can be difficult to maintain a good overlap of the acoustic detection and the optical excitation [2]. In contrast, the optical hydrophone offers a large transparent window enabling fast optical scanning through the sensor without the necessity to mechanically move the sensor (Fig. 5). The acoustic coupling is maintained with a drop of water or ultrasound gel between sample and sensor.

A photoacoustic image of a zebra fish larva, measured by the optical hydrophone, is shown in Fig. 6. This picture

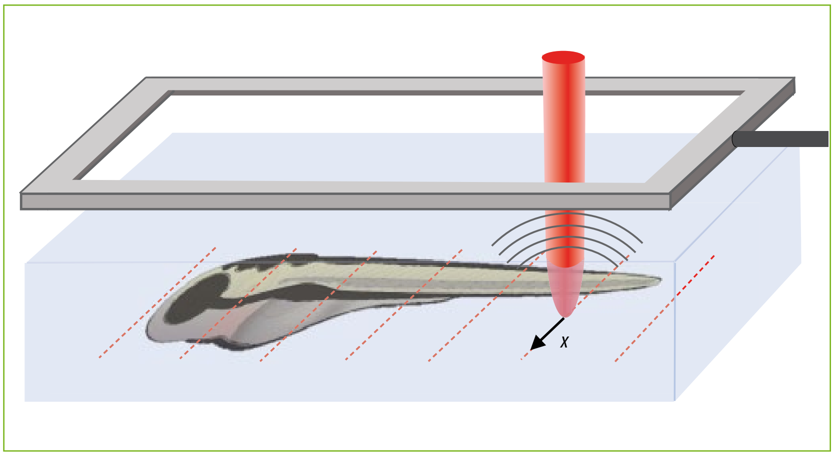

Fig. 5 Measurement principle of photoacoustic microscopy in reflection-mode. Zebrafish larva anesthetized in tricaine and embedded in agar (blue) are scanned by a focused laser beam (red) and the photoacoustic waves are detected by the optical hydrophone (gray).

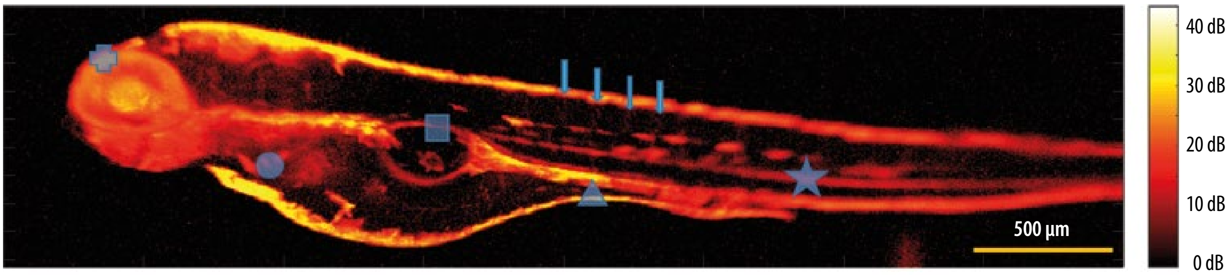

Fig. 6 Photoacoustic microscopy image using the optical hydrophone, showing a propylthiouracil-treated zebrafish larva, 120 hours after fertilization. The color bar indicates the SNR in decibels. Blue arrows: intersegmental vessels; blue square: swim bladder; blue cross: eye; blue circle: heart; blue star: dorsal aorta; tip of blue triangle: axial vein. Figure taken and adapted from [5].

results from a multimodal imaging microscope, which combines optical coherence and photoacoustic microscopy (OC-PAM), providing complementary information for imaging biological tissues [5].

In the maximum intensity projection of PAI measurements on zebrafish larvae (Fig. 6), strong absorption differences based on chromophore distributions can be seen. The OC-PAM system allows fast, high-resolution imaging, which is important for many studies towards improved cancer medication, or to even investigate the mechanisms behind diseases such as diabetes.

Wide-ranging applicability for liquid- and airborne ultrasonics

The presented examples are an excerpt of the novel optical sensor's scope. In PAI and sound-field characterization, the optical sensor is used as a hydrophone, for which size and sensitivity are nearly independent parameters. Therefore, further miniaturization of the sensor will enable photoacoustic endoscopy applications, where highly sensitive detection combined with small element size is of particular importance. The very small active sensing area of 0.01 mm^2 allows for spatially high-resolving sound field scans.

Today, the sensor is also being used for air-coupled ultrasound detection, as a microphone. Apart from medical engineering, this opens the field to even further applications such as acoustic industrial process control and non-destructive material testing.

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[1] *G. Harvey, A. Gachagan, T. Mutasa:* Review of high-power ultrasound-industrial applications and measurement methods. IEEE Trans Ultrason Ferroelectr Freq Control (2014), **61**(3)

[2] *S. Preisser* et al.: All-optical highly sensitive akinetic sensor for ultrasound detection and photoacoustic imaging. Biomedical Optics Express (2016), **7**(10)

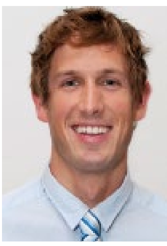
[3] *J. Yao & L.V. Wang:* Sensitivity of photoacoustic microscopy. Photoacoustics (2014), **2**(2)

[4] *C. Li & L.V. Wang:* Photoacoustic tomography and sensing in biomedicine. Phys. Med. Biol. (2009), **54**(19)

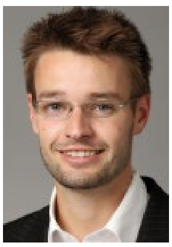
[5] *R. Haindl et al.:* Dual modality reflection mode optical coherence and photoacoustic microscopy using an akinetic sensor. Optics Letters (2017), **42** (21); 4319-4322-1

Author

Stefan Preißer studied physical engineering at the Coburg University and biomedical engineering at the Leibniz University in Hannover. After receiving his PhD in physics from the University of Berne (Switzerland) he joined a cooperation project between Xarion Laser Acoustics and the Medical University of Vienna as a postdoc. The project successfully demonstrated photoacoustic microscopy with the optical microphone. He is continuing his research in this field as a principal investigator since 2016.



Balthasar Fischer was born in Switzerland, where he studied physics. He moved to Vienna in 2001 to complete a Tonmeister degree at the University of Music. He received his PhD in photonics from Vienna University of Technology, before joining Philips Sound Solutions as R&D member. In 2012, Balthasar founded Xarion Laser Acoustics, based on his invention, the membrane-free optical microphone. In the course of his career, he has won several awards, including the Fehrer Prize and the Leibinger Innovation Award.



Nils Panzer studied mechanical engineering and management at Technical University of Munich, completing a Diploma in the field of production technology. Since 2015, he is studying medicine at Medical University of Vienna. He joined Xarion for the development of sensor applications in industrial and medical fields.

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