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Thomas Kirchner, Claus Villringer, Marko Gutke, Jan Laufer, "Plano-concave optical sensor for transcranial photoacoustic measurements," Proc. SPIE 12631, Opto-Acoustic Methods and Applications in Biophotonics VI, 126310R (11 August 2023); doi: 10.1117/12.2675593

SPIE.

Event: European Conferences on Biomedical Optics, 2023, Munich, Germany

Plano-concave optical sensor for transcranial photoacoustic measurements

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ABSTRACT

Biomedical photoacoustics is usually used to image absorption-based contrast in soft tissues up to depths of several centimeters and with sub-millimeter resolution. By contrast, measuring photoacoustic (PA) signals through hard bone tissue shows severe signal degradation due to aberration and high attenuation of high frequency acoustic signal components. This is particularly noticeable when measuring through thicker, human, skull bone. Which is the main reason why transcranial PA imaging in humans has so far proved challenging to implement. To tackle this challenge, we developed an optical resonator sensor based on a previous planar-concave design. This sensor was found to be highly suitable for measuring the low pressure amplitude and low acoustic frequency signals that are transmitted through human cranial bone. A plano-concave optical resonator sensor was fabricated to provide high sensitivity in the acoustic frequency range of DC to around 2 MHz, a low noise equivalent pressure and a small active element size enabling it to significantly outperform conventional piezoelectric transducers when measuring PA waves transmitted through *ex vivo* human cranial bones.

Keywords: Photoacoustics, transcranial, optical resonators, *ex vivo*, human skull

1. PURPOSE

Our overall goal is to investigate the feasibility of transcranial photoacoustic (PA) sensing and imaging of the human brain, specifically the monitoring of hemodynamics and the detection of intracranial bleeding. The main challenge for human transcranial photoacoustics is the acoustic attenuation and wavefront aberration in the bone.¹ This effect is frequency dependent² – frequencies higher than approximately 1 MHz are prohibitively attenuated by thick human cranial bone.

In this study we focus on the development of a novel sensor for transcranial PA signals, building on previous work by Guggenheim et al.³ We present the characterization work on one of the produced sensors and the initial results from PA sensing through *ex vivo* human skull.

2. MATERIALS & METHODS

We designed, fabricated and characterized one a plano-concave optical resonator sensor and compared its performance in transcranial PA measurements to two large diameter, low frequency, commercial piezo-ceramic transducers.

Human skull sample We measured PA waveforms through the frontal bone of an *ex vivo* skull of a typical 70 year-old male body donor.⁴ The skull sample was immersed in degassed deionized water for at least 15 minutes prior to measurements. The water bath was kept at room temperature of 23 °C, during all measurements.

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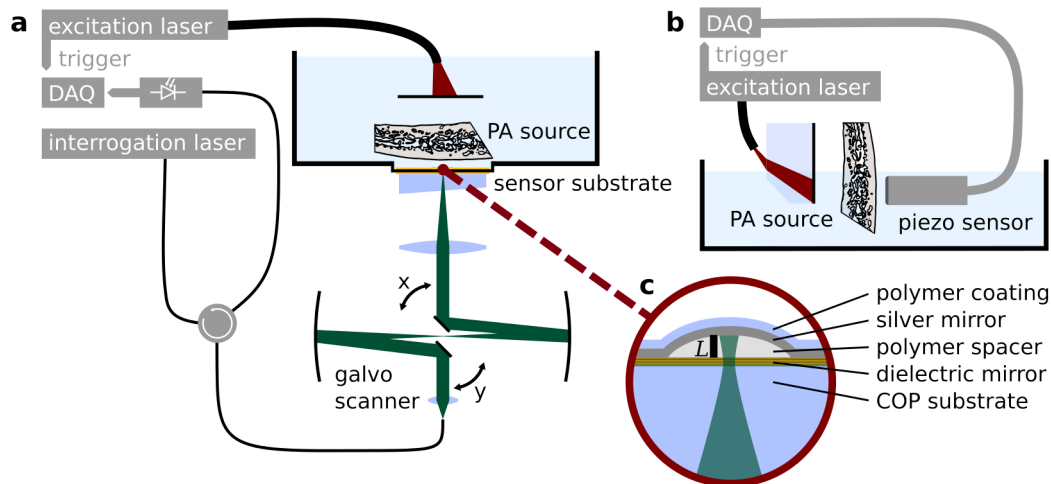


Figure 1. **a** Experimental setup for optical interrogation of a substrate with plano-concave optical resonator sensors. Transmission experiment on *ex vivo* human skull. A thin acrylic black paint film on PMMA served as a target absorber and PA source which was directly illuminated by the excitation laser. **b** The experimental setup for acoustic transmission measurements using piezoelectric immersion transducers. **c** Schematic of a single plano-concave optical resonator with spacer thickness L at the point of interrogation.

Optical resonator sensor fabrication The Optical resonator, shown in figure 1c, was produced on a cycloolefin polymer (COP) substrate (made from ZEONEX 480R, by Polymeroptix, Goch, Germany). First a dichroic mirror was deposited on the substrate, combining layers of SiO_2 and TiO_2 with magnetron sputtering (LS 730 ES, Von Ardenne, Dresden, Germany). The polymer spacer (OrmoClad, Micro Resist Technology, Berlin, Germany) was placed on the completed first mirror as a droplet, cured with UV light, tempered and cured again. The second mirror was made of silver, deposited with DC magnetron sputtering. A parylene-C coating was applied to prevent water damage. The prototype plano-concave optical resonator sensor presented in this work has a physical cavity thickness of $L = 493 \mu\text{m}$.

Transcranial *ex vivo* experiments and characterization setup We measured transcranial PA waveforms with our plano-concave optical resonator sensor, interrogating them with a galvo scanner setup shown in in figure 1a.^{5,6} The interrogation laser is a tunable diode laser (T100S, Yenista Optics, Lannion, France) with a maximum output power of 8 mW in the utilized range of 1591 nm to 1594 nm. It is focused to a $30 \mu\text{m}$ beam waist at the optical resonator. The reflected power is passed through an optical circulator into an InGaAs photodiode (G9801-22, Hamamatsu Photonics, Japan). The photodiode output signal is cut to AC and DC components at 100 kHz. The AC component data acquisition (DAQ) is done by a digital oscilloscope (PCI-5124, National Instruments, USA) which is triggered by the excitation laser. The DC component is measured via a digital I/O card and BNC adapter (PCI-6229 with BNC 2110, National Instruments, USA). The galvo scanner mirrors (GVS012, Thorlabs, Newton, USA) are controlled using that same I/O card. A 1064 nm Nd:YAG laser (Nano L 150-50, Litron Lasers, Rugby, UK) with 50 Hz pulse repetition rate produced excitation pulses of 7 – 9 ns pulse width.

We measured the PA waves generated in a thin black acrylic paint coating on a 2 cm thick PMMA slab. The coating was illuminated directly with 5 mm beam diameter and approximately 2 mJ per excitation pulse. This generated broadband acoustic waves.

For comparison we performed similar experiments with two unfocused single element piezo-ceramic, lead zirconium titanate (PZT) sensors: one with a center frequency of 500 kHz (V301-SU, Olympus, Waltham, USA)

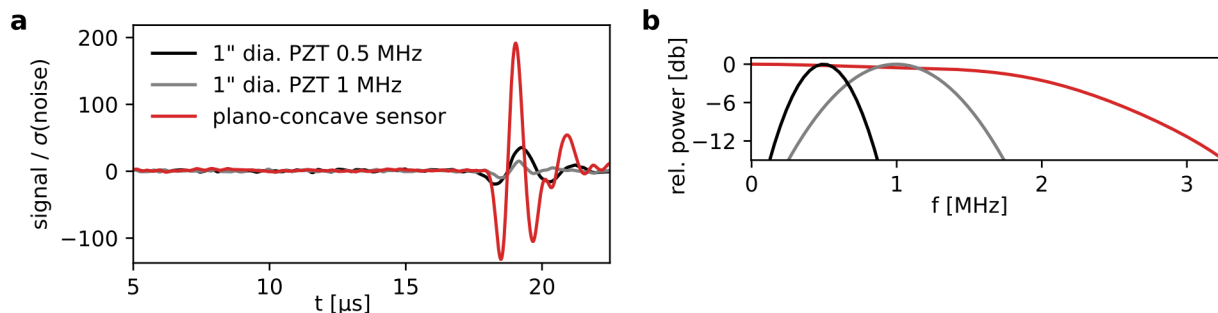


Figure 2. Transcranial PA sensing through *ex vivo* human frontal cranial bone. **a** Waveforms measured with single element sensors, low-pass filtered and scaled to the standard deviation of noise. **b** The theoretical acoustic sensitivity spectra for the sensors used.

and one 1 MHz transducer (V302-SU), using a separate data acquisition unit (Flash ADC, PhotoSound, Houston, USA) as shown in figure 1b. Both transducers have 65 % bandwidth and a 25.4 mm active diameter.

3. RESULTS & DISCUSSION

Figure 2a shows an example of the initial transcranial PA sensing results for one of our plano-concave optical resonator sensors together with the signal response for two piezo-ceramic PZT sensors. These waveforms are shown post-processed using the same low-pass filter to make the noise spectra comparable – a second order Butterworth filter with a cut-off frequency of 3 MHz.

Piezo-ceramic sensors are generally thought to be most sensitive, and are almost exclusively used for deep PA imaging and sensing. The results in figure 2a suggest that optical sensors can be used to measure transcranial PA signals in adult humans, even through the thickest skull. In *ex vivo* measurements, the presented plano-concave optical resonator sensor shows higher signal to noise compared to the PZT sensors. This is despite a large discrepancy in active element size (PZT sensors: 25.4 mm diameter, plano-concave sensor: 60 μ m diameter).

Our comparatively thick³ plano-concave optical resonator sensor has three highly advantageous properties: The thick spacer and concave resonator leads to (1) a low noise equivalent pressure (NEP) of approximately 1 Pa, measured at 1 MHz and (2) a theoretically flat acoustic sensitivity spectrum from DC up to 2 MHz as shown in figure 2b. (3) The small active area of the optical resonator sensors excludes spatial averaging of the strongly aberrated transcranial signals.

4. CONCLUSIONS

We have shown first results which indicate that plano-concave optical resonator sensors may be well suited for transcranial PA measurements in adult humans.

ACKNOWLEDGMENTS

This work was funded by the German Research Foundation (DFG, Deutsche Forschungsgemeinschaft) under grant number 471755457. We thank Heike Kielstein, Institute of Anatomy and Cell Biology, MLU Halle-Wittenberg for the provision of the human skull sample; and Werner Lebek of the Medical Physics Department, MLU Halle-Wittenberg for the application of the protective coating.

AUTHOR CONTRIBUTIONS

TK: Conceptualization, Data curation, Formal analysis, Investigation, Funding acquisition, Implementation, Validation, Visualization, Software, Writing – original draft. CL and MG: Methodology and Implementation (for plano-convex optical resonator fabrication). TK and JL: Methodology, Supervision, Project administration and Resources (also see non-author contributions in acknowledgements.) TK, CL, MG and JL: Writing – review & editing.

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