Miniature and non-contact photoacoustic system using silicon photonics-based Laser Doppler Vibrometer and compact excitation source

(Student paper)

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Conventional photoacoustic (PA) systems use bulky high-power excitation laser sources and ultrasonic transducers that need to be in contact with the sample, and hence have many application limitations. In this paper, we present photoacoustic measurements using a small silicon photonics-based Laser Doppler Vibrometer (LDV) and a compact pulsed laser diode. The successful demonstration indicates that a compact and contactless PA system is possible.

Keywords: *Photoacoustics, Laser Doppler Vibrometer, Silicon Photonics*

INTRODUCTION

In recent years, photoacoustic systems have been demonstrated to improve upon existing solutions by combining the benefits of light and sound, particularly in biomedical applications where conventional optical imaging is limited in depth by scattering [1,2,3]. In conventional photoacoustic systems, a pulsed excitation laser is directed toward a sample. There, the excitation light absorbed in the sample is converted into an acoustic wave through the photoacoustic effect. The resulting acoustic waves, which can be detected by using an array of detectors, give information about the light absorption inside the sample. The spatial origin of the acoustic wave can be determined with proper algorithms. Using different excitation wavelengths, the spectral information of the absorption profile can also be obtained [2,3]. One important application where multiple excitation wavelengths are used in the biomedical domain is determining the oxygenation profile inside tissue [4].

Most often, contact-based detectors (such as piezoelectric or optomechanical sensors [5]) are used for detecting ultrasound waves. Here, contact-based methods such as physical contact, a coupling medium, or immersion of the sample are necessary due to a large impedance mismatch between the air and the sample [6]. For many applications, especially in the biomedical domain, these contact methods are impractical or create a risk of contamination of the sample [7]. Optical techniques such as Laser Doppler Vibrometry (LDV) provide a non-contact alternative to detect the vibrations at the surface of the sample caused by the photoacoustic pressure wave [8]. Photoacoustic imaging applications often need detection at multiple locations on the sample. For LDV however, increasing the number of sensing locations increases the number of optical elements and complexity, resulting in an expensive and bulky detector system. Here, we demonstrate a system using a silicon photonic integrated circuit to enable non-contact and compact photoacoustics [9]. Using CMOS-like techniques, most of the passive optical components and interconnecting waveguides can be integrated onto a small silicon chip [10,11]. Hereby enabling relatively low cost (for medium to large-volume production) and very compact (< few mm^2) LDV systems, even for multi-beam LDVs.

A compact and contactless photoacoustic system requires a compact photoacoustic excitation source. In photoacoustic demonstrations, usually a bulky and expensive high-power pulsed laser source is used as the excitation laser (e.g. Nd YAG Lasers, …). These lasers can provide short pulses (<10 ns) with high pulse energy (>1 mJ) and therefore provide a large photoacoustic signal. In recent years, laser diode- and LED-based pulsed sources were suggested as a compact and relatively inexpensive alternative [12].

In this paper, we combine, for the first time, the use of a silicon photonic LDV with a compact pulsed laser diode to demonstrate compact and non-contact photoacoustics. We detect the photoacoustic responses of a target embedded in a silicone sample that mimics the acoustic properties of biological tissue. We show that we can detect photoacoustic signals from absorber concentrations in the physiological range for blood.

METHODS

Figure 1a shows a schematic of the setup used in this paper. In figure 1b, a schematic layout of the on-chip homodyne LDV is depicted. An external 1550 nm laser couples light into the chip through a fiber glued to a grating coupler. On the chip, the light is split into a measurement and reference beam. The measurement beam goes to a transmitting antenna and is directed toward a target. After reflection upon the target, the measurement light is collected again on the photonic integrated circuit (PIC) and there the light is combined with the reference light in a 90-degree optical hybrid. In the hybrid, the measurement and reference light are combined into multiple light signals with a relative phase shift of 90 degrees between them. Four photodetectors at the output of the hybrid convert the intensity, resulting from interference, into electrical signals. From these photocurrents, in-phase and quadrature signals can be obtained and the phase difference between the reference and measurement beam can be demodulated. Here, we designed the amplifier electronics with a bandwidth of 3 MHz. Assuming a non-moving chip, we can record the movement of the target due to the path length change of the measurement beam. The measurement beam was focused onto the silicone sample and aligned such that specular reflection was collected.

As the source, a pulsed laser diode package at 905 nm (OSRAM SPL S4L90A_3 A01) was mounted on a pulsed driver (LDP-V 240-100) (as can be seen in figure 1d). During experiments, the laser driver provided 500 ns pulses of 160 A at a repetition rate of 1 kHz to the laser diode package, resulting in pulses of 250 µJ with a peak power of around 500 W at a repetition rate of 1 kHz. The diode was placed around 3 mm from the silicone sample and without additional focusing optics.

The silicone sample has an approximate thickness of 1cm ± 1mm. A channel with a diameter of 3 mm lies at a depth of 5 mm ± 1.5 mm. The channel can be filled with different water-based ink solutions to change the absorption. Here, we used black India ink solutions of 0.01%, 0.05%, and 0.10%. From a measured spectrum, it is estimated that this agrees respectively with an absorption coefficient of 1.2 cm^{-1}, 6 cm^{-1}, and 12 cm^{-1}.

For the measurements, we record for 10 seconds with triggered acquisition for each excitation source emission (at 1 kHz) and through averaging of the 10000 segments, we obtain the results shown in figure 2.

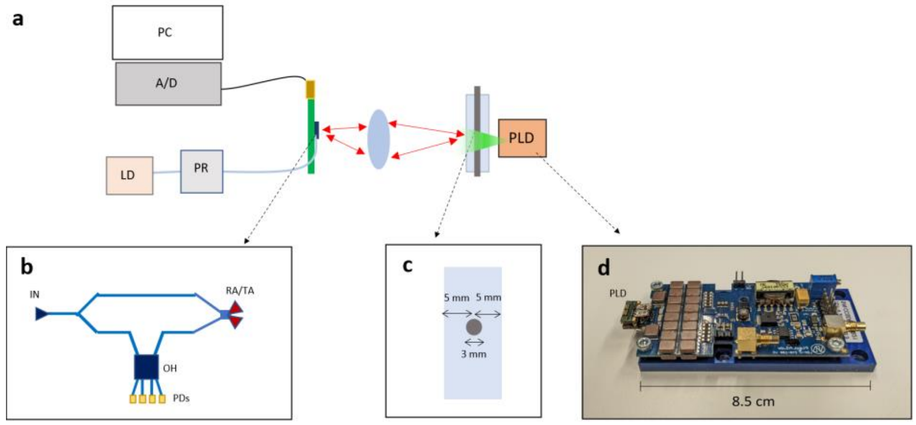

Fig. 1 a) Schematic of photoacoustic setup. A 1550 nm laser diode (LD) is connected to the PIC after going through the polarization rotator (PR). The signals from the LDV system get digitized through an analog-digital converter (A/D) connected to a PC. A pulsed laser diode (PLD) is used as a compact and miniature excitation source. b) Schematic depiction of on-chip homodyne LDV, consisting of: Input grating coupler (IN), receiving and transmission antennas (RA/TA), optical hybrid (OH) and the on-chip photodetectors (PDs) c) Schematic depiction of the silicone sample with dimensions and an embedded ink channel. d) Picture of the compact electrical driver and pulsed laser diode.

RESULTS

Figure 2 shows the velocity signal recorded by the on-chip LDV. Time 0 indicates excitation source emission. As can be seen, the excitation of the laser diode induces a response in the detection system. This is due to electrical and or optical interference from the excitation and detection system. Around 7 to 8 µs after the excitation, a photoacoustic response is detected. From figure 2, it can also be seen, especially for higher concentrations, that another smaller response appears around 7 to 8 µs after the initial photoacoustic response. This is the reflection of the acoustic wave, from the excitation side of the silicone sample, whereby the polarity of the pressure wave has switched, as expected for an acoustic reflection at a solid-air interface. Considering a sound velocity of 1000 µm/µs for silicone [14], and given that the absorption happens mostly on the excitation side of the tube, the time delays match reasonably well with the propagation distances. Small differences can be expected due to the variance in the dimensions of the sample, variance in the speed of sound, and small misalignment of the detection beam.

From figure 2 it can be seen that the lowest concentration where a signal could be measured was for a 0.01% solution. From the absorption spectrum of India ink, it was estimated that the absorption of the solution is around 1.2 cm^{-1}. This is within the physiological absorption range of blood at NIR wavelengths (1-10 cm^{-1}).

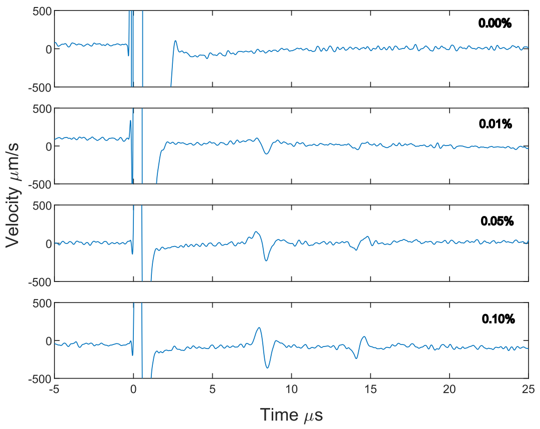

Fig. 2 Photoacoustic response measured by the LDV system from the silicone sample for different black India ink solutions in the channel through the silicon sample inside the sample. Time 0 indicates excitation source emission, and a photoacoustic response is detected around 7 µs after excitation. A second reflection from inside the sample is detected around 14 us.

DISCUSSION

In this paper, we detected photoacoustic signals from a tissue-mimicking sample using a silicon photonics-based LDV and a compact excitation source. The optical chip uses interference to detect the photoacoustic vibrations at the surface of the silicone sample and was able to get a photoacoustic response for a target with an absorption well within the physiological range of blood (as low as 1.2 cm^{-1}) [15]. In the photoacoustic system, a pulsed laser diode was used as a compact excitation source. This paper demonstrates the feasibility of a compact contactless photoacoustic system using silicon photonic LDVs and compact excitation source.

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