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Silicon photonics based Laser Doppler Vibrometer for non-contact photoacoustic sensing

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ABSTRACT

Non-contact detection of photoacoustic signals is important for various applications, particularly in medical sensing and imaging, where contact methods can be uncomfortable or risky for the patient. Techniques using optical detection of vibrations, such as laser doppler vibrometers (LDVs), have been proven to be a key component for enabling non-contact photoacoustic sensing. However, most LDV systems rely on fiber-based or free-space optics, which can be unwieldy and expensive, especially for multiple location sensing. In this work, we present a compact, photonic integrated circuit (PIC)-based homodyne LDV system for the detection of photoacoustic signals. The system is fabricated on a silicon-on-insulator platform, which has the potential to be low-cost in case of medium or large volume production. To generate the photoacoustic signals, we used a 532 nm pulsed laser directed towards a target embedded in a silicone phantom designed to mimic the acoustic properties of human tissue. The target consists of an ink-solution-filled channel, which absorbs the excitation light and generates acoustical signals within the phantom through the photoacoustic effect. After performing a series of measurements with different ink concentrations, we found a good correlation between the photoacoustic signals detected by the on-chip detectors and the absorption of the target. Our system was able to detect ink solutions with absorption values as low as 5 cm^{-1}, an order of magnitude lower than the typical absorption of whole blood at 532 nm. These results demonstrate that PIC-based LDVs can be used to realize compact and low-cost non-contact detection for photoacoustic biomedical sensing applications.

Keywords: Photoacoustics, Laser Doppler Vibrometer, Silicon Photonics

1. INTRODUCTION

Over the last decade, photoacoustics has proven to be an important technique for different sensing and imaging applications, especially in the biomedical domain[1,2] . By combining the properties of light and sound, photoacoustics allows for the imaging and sensing of light absorption at significant depths (up to a couple of cm in biological tissue).[3] In photoacoustic biomedical applications, typically, a nanosecond pulsed laser irradiates a sample or tissue. Inside the sample, the light scatters and gets absorbed. The local absorption causes transient heating, which leads to the generation of ultrasound waves through the thermo-elastic effect. These waves propagate through the sample and can be detected at the surface. By using multiple excitation wavelengths, spectral information about the absorption in the sample can be obtained.

Conventional methods for detecting ultrasound waves rely on a piezoelectric transducer or an array of them. Recently, optomechanical detectors have also been proposed as suitable detectors for photoacoustics.[4] However, for both type of detectors, the large acoustical impedance mismatch between tissue and air requires the use of techniques such as physical contact, the use of a coupling medium, or immersion of the sample.[5] These techniques can be impractical and increase the risk of contamination or reaction with the sample.[6] This is a major drawback for many biomedical applications.

In recent years, various optical techniques have been developed for the non-contact detection of photoacoustic signals.[7] Speckle analysis uses changes in the interference pattern detected by a CCD camera of the reflected light to detect vibrations.[8,9] However, this method has a limited bandwidth and can be prone to noise due

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to spurious motions. Non- interferometric photoacoustic remote sensing is a more recent technique that has demonstrated good detection sensitivity for non-contact photoacoustic microscopy.[10,11] This technique uses con-focal excitation and measurement light that is reflected off the sample. The reflected intensity is modulated due to the change in refractive index due to local heating and expansion. This method directly probes the local photoacoustic response, but can only provide A-scan information through optical sectioning. Interferometric techniques, on the other hand, measure the phase of the reflected light and can provide both A-scan information through high-bandwidth signal detection.

Laser Doppler vibrometers (LDVs) have also been used to detect photoacoustic signals.[12–14] These systems are typically based on free-space or fiber optics, which can be expensive and bulky. In this work, we present a photonic integrated circuit (PIC)-based homodyne LDV for compact, optical-based detection of photoacoustic signals.[15] The PIC is fabricated on a silicon-on-insulator platform, which allows for the miniaturization of various optical systems using CMOS-compatible techniques.[16] This platform has the potential to be low-cost in case of medium- to high-volume production. The design and operation of the PIC-based LDV will be described in the following section.

Hereafter, we describe the photoacoustic setup and present measurements taken on a sample mimicking the acoustic properties of tissue. We demonstrate a linear correlation between the vibrations measured by the PIC-based LDV and the concentration of absorbers.

2. METHODS

2.1 Silicon Photonics based Laser Doppler Vibrometer

The PIC-based laser doppler vibrometer (LDV) used in this study is based on a homodyne interferometer design (as depicted in figure 1a). C-band light is coupled into the chip through an optical fiber which is glued after alignment. Then the light is split into a measurement and reference arm. The light in the measurement arm is directed towards a grating-coupler based transmission antenna. Here, the measurement light is coupled out from the chip and focused on the target with an optical lens system. After reflection from the target, the light is coupled back into the chip through the grating coupler. Then the measurement light is combined with reference light in an 90 degree optical hybrid with four output waveguides feeding into four on-chip photodetectors.

The PIC is connected to a printed circuit board (PCB) through wire bonds to the on-chip photodiodes and other bond pads on the chip. The photodiode signals are differentially amplified on the amplifier PCB and two signals in quadrature are obtained and digitized. From the I and Q signals, one can demodulate to get the phase information of the measurement beam. The phase difference $\Delta\phi(t)$ can be related to the targets displacement $\Delta d(t)$ through this expression;

$$\Delta d(t) = \frac{\lambda \Delta\phi(t)}{4\pi} \tag{1}$$

Ideally, the I and Q signals constitute a circle with the origin at 0 when displacing the target. In practice however, fabrication errors of the chip and asymmetry in the amplifiers or photodetectors give rise to spurious effects resulting in ellipse-like IQ shapes with their center not at the origin. In order to more accurately demodulate, we use the Heydemann correction,[17] which uses a fit of an ellipse to the recorded IQ-data and then transforms the recorded values such that the fitted ellipse becomes the unit circle. Hereafter, the arctangent demodulation retrieves the phase and the target's displacement.

2.2 Sample and Setup

In many biomedical photoacoustic applications, blood is a vital contrast agent.[1] To minimize absorption of the photoacoustic excitation light by water, visible to near-infrared (NIR) wavelengths are often used as the excitation source. In this range, absorption spans three orders of magnitude from 10^0 cm^{-1} to 10^3 cm^{-1}.[18,19] In this study, we use a frequency doubled, diode pumped Q-switched laser (EKSPLA NL202), resulting in a 532 nm pulsed laser source emitting 1.43 mJ pulses with a pulse length of 7 ns. Water-based solutions of black India ink are used as absorbers to mimic the absorption values of blood at 532 nm. These absorption values range from 1 cm^{-1} to 50 cm^{-1}, similar to the values of blood absorption.

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A schematic of the setup can be seen in figure 1c. The excitation and detection were performed on opposite sides of the sample.

The absorption spectrum of blood depends on its oxygenation levels, allowing the latter to be determined using photoacoustic measurements with multiple excitation wavelengths.[18] Determining and imaging local oxygenation is a crucial application of photoacoustics, as it has been shown to be important for cancer studies,[20,21] brain studies,[22] wound healing,[23] and more.

To demonstrate the ability to quantitatively determine oxygenation levels or for other spectroscopic photoacoustic applications, we have created a sample that allows us to alter the absorber concentration by changing the ink concentration. Figure 1b shows a drawing with the dimensions of the sample. The sample is made of silicone that emulates the properties of biological tissue, with a speed of sound of around 1000 m/s,[24] while in tissue it is around 1500 m/s.[25] Acoustic scattering is minimal and can be neglected. To create the sample, silicone and hardener were mixed and poured around Teflon tubing embedded in a mold. After hardening, the Teflon tubing was removed, resulting in a silicone sample with a thickness of approximately 1 cm $\pm$ 1 mm and channels with a diameter of around 3 mm. Different, ink solutions can be introduced into the channels through tubes connected to the edge of the sample, allowing to look at the photoacoustic reponse for different concentrations of the absorber.

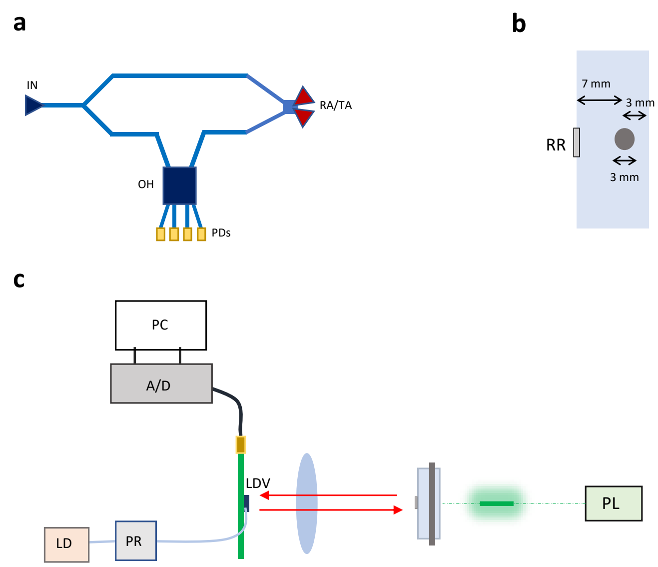

Figure 1. a) Schematic depiction of on-chip homodyne LDV, consisting of: Input grating coupler (IN), receiving and transmission antennas (RA/TA), optical hybrid (OH) and the on-chip photodetectors (PDs). b) Dimensions of silicone sample with embedded, an ink-solution filled channel and a retro-reflective tape (RR). c) Shematic depiction of photoacoustic setup. A pulsed laser (PL) is directed towards a target, on the other side, the LDV system sends signals to an analog-digital converter (A/D) connected to a PC. A 1550 nm laser diode (LD) is used as light source powering the PIC after polarization rotation (PR).

3. RESULTS AND DISCUSSION

In Fig. 2a, one can see the measured photoacoustic response by the on-chip LDV of the silicone sample filled with 0.075 % ink-water solution. The signal was obtained after averaging for 10 seconds at a repetition rate of 1 khz. At time=0 the excitation laser emitted the pulse. The response at time 0 is due to the detector system response of the high power pulse emitted by the excitation laser. At around 8 μs, the photoacoustic pulse from the ink absorption arrives at the surface and is detected by the on-chip LDV. Based on a velocity of around 1000 m/s, the distance travelled by this pulse is around 8 mm. This agrees with the actual travelled distance which is 8.5 $mm \pm 1.5$ mm, taking into account the width of the channel. At 13.5 μs another, smaller response

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is detected. This time delay indicates that this response originates from the reflection of the photoacoustic pulse at the excitation side of the sample. There is a 5.5 μs difference between the second and first response. Using a speed of 1000 m/s, this relates to a distance of 5.5 mm due to the increased amount of travelled distance retrieved form the increase in time delay, which agrees with the expected added travelled distance by a signal reflected from the back first ($6\ mm \pm 1.5\ mm$).

From the photoacoustic time response, we can estimate the depth of the of the excited ink. The response amplitude gives information about the excitation absorption from the filled channel. In 2b, the peak to peak amplitude of the photoacoustic response at 8 μs is plotted for different ink concentrations. As can be seen from the figure, a linear correlation can be observed.

From these results, it can be seen that it is possible to measure photoacoustic responses of ink concentrations below 0.02 %. From the measured spectrum, it is estimated that this agrees with an absorption of around 5 cm^{-1} at 532 nm.

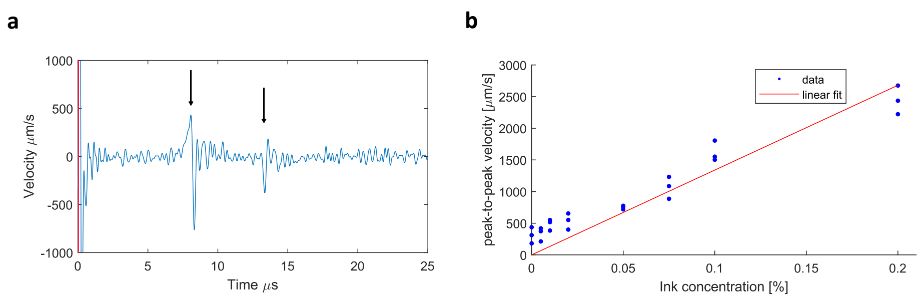

Figure 2. a) Photoacoustic signal recorded by the on-chip LDV of 0.075 % ink-water solution inside the silicone sample. b) Peak-to-peak velocity from the photoacoustic response around 8 μs after laser emission for different ink concentrations, indicating a linear correlation between ink concentration and response amplitude

4. CONCLUSION

We demonstrated the feasibility of using a silicon photonics-based LDV to remotely detect photoacoustic signals with good sensitivity and linear correlation with absorber concentration. The compact optical sensor is an interferometer fabricated on the silicon on insulator platform. We used a silicone sample that mimicked the acoustical properties of tissue, and embedded an ink solution-filled channel in the sample as the absorbing target. The sample was irradiated with a high power pulsed laser excitation source. By measuring the amplitude of the photoacoustic signal with the on-chip LDV, we observed a linear correlation with the target absorption. We were able to detect ink concentrations as low as 0.02 %, corresponding to an expected absorption of around 5 cm^{-1} at 532 nm. This is an order of magnitude lower than the typical absorption of whole blood at the same wavelength. Additionally, we extracted A-scan information from the time profile of the measured signals by analyzing the arrival time delays of the photoacoustic signals. These results show the potential of using compact, silicon photonics-based LDVs for photoacoustic sensing applications, including biomedical sensing and imaging.

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