Proposal for non-contact photoacoustics using silicon photonics-based Laser Doppler Vibrometers

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Photoacoustics has proven to be an important technique for realizing new sensing and imaging solutions. Conventional methods rely on an ultrasound detector in contact with the sample. Contact-based methods increase however the risk of contamination or reaction with the sample. This is a major drawback for many applications, especially in the biomedical field. Interferometric techniques have proven to enable non-contact photoacoustics, but these free-space or fiber-based systems are usually too bulky. In this paper, we present silicon photonics-enabled on-chip Laser Doppler Vibrometers (LDV) as a compact and non-contact solution for photoacoustic sensing or imaging. A design of silicon photonics-based LDVs is proposed and its performance is analyzed and compared to other ultrasound detector solutions for non-contact photoacoustics. From these performance metrics, we discuss the benefits and limitations of LDVs for the detection of photoacoustic signals and propose how an on-chip LDV array can provide compact and non-contact photoacoustic imaging.

Introduction

In the last decade, it has been demonstrated that photoacoustic techniques can enable new biomedical sensing and diagnostic tools to go beyond conventional techniques [1]. In photoacoustics, a modulated or pulsed laser excitation source illuminates a sample that may contain a part that can strongly absorb the excitation light. Because of the photo-thermal effect, local heating occurs where the light is absorbed. This local heating induces a sudden local stress which will be propagated to the surface of the sample as an acoustic wave. The acoustic waves can be detected and processed to retrieve the absorption profile of the excitation source [2]. This combination of optical excitation and acoustical detection allows for retrieving the absorption information far beyond the ballistic regime, which is usually the limit in conventional optical imaging systems relying on optical reflection (e.g. optical coherence tomography, optical imaging,…). Using multiple different excitation wavelengths, spectroscopic information can be retrieved from the absorption profile at different wavelengths.

A photoacoustic system for biomedical applications requires sensitive and compact ultrasound detectors. Due to a large impedance mismatch between air and sample, and very poor ultrasound transmission in air, conventional ultrasound detectors require to be in contact with the sample and often, a contact gel is used to improve ultrasound transmission from sample to detector [3]. In biomedical applications, contact with any sample creates a risk of infection and contamination [4]. In recent years, laser doppler vibrometers (LDV) have been used to demonstrate non-contact photoacoustics [5]. In this interferometric technique, a beam of light probes the movement of a remote target. These optical systems consist of several optical elements such as splitters/combiners, optical hybrids, photodetectors… Usually, these systems are made using free space optics or fiber-based components. However, increasing the number of probe beams drastically increases the number of optical elements and fibers and increases complexity, cost, and size. In this paper, we propose silicon photonics-based LDVs as a non-contact and compact solution for photoacoustic applications, even with multiple probe beams. Silicon photonics uses CMOS-like techniques to create optical components and waveguides on a small silicon chip [6]. For medium to large-volume production, the cost of a chip can be relatively low. It also allows the creation of on-chip LDVs with multiple probe beams on a chip smaller than 1 mm^2 [7]. In the next part, we introduce the on-chip LDV working principle and calculate the theoretical limits of on-chip LDVs. Thereafter, we discuss the benefits and drawbacks of using on-chip LDVs for photoacoustic biomedical applications.

Silicon photonics-based LDVs

The general layout of an on-chip homodyne LDV is depicted in figure *1*a. An external laser couples light into the chip using a grating or edge coupler. The coherent light is split into a reference beam measurement beam. The measurement light goes to a transmitting antenna to direct light toward a target. After reflection from the target, the collected light is combined with the reference light into a 90° optical hybrid. On-chip photodetectors connected to each port of the hybrid convert the intensity into currents. From these photocurrents, one can retrieve a pair of signals with a quadrature phase relation (i.e. I and Q signals). After a demodulation procedure, the phase difference between the reference and measurement beams can be obtained. A change in the phase difference denotes a change in the path length and the displacement can be retrieved. When the chip remains static, we can thus remotely record the movement of the target. As seen in figure 1b, recent demonstrations include a six-beam silicon photonic-based LDV system and indicates the potential for on-chip silicon photonics LDV with multiple beams [8].

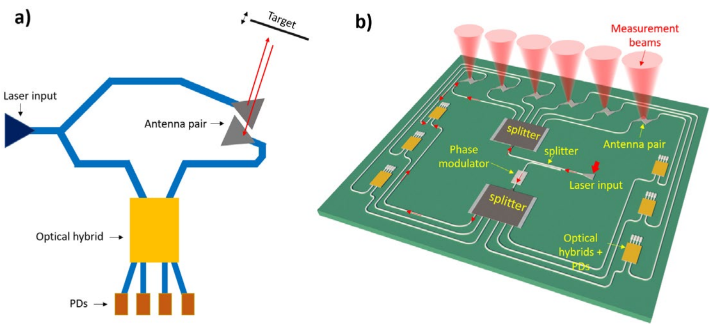

Figure 1 a) Schematic of an on-chip LDV layout b) Reproduced from [8],layout of a six beam on-chip LDV

Assuming a homodyne LDV limited by the shot noise in the photodetector, one can estimate the noise limit of an LDV, as can be seen in Figure 2. Considering a white noise spectrum of the shot noise, this results in a flat phase- and flat displacement noise spectrum. The flat displacement noise spectrum can be translated into a linearly increasing velocity noise spectrum, and using a specific acoustic impedance this can be converted into a pressure noise spectrum. The following equation describes the relation between the sample-air boundary velocity (u) and the pressure amplitude of an incident acoustic plane wave (p), through the specific acoustic impedance of the sample (Z_{sample}), assuming $Z_{sample} \gg Z_{air}$.

$$p = \frac{Z_{sample}}{2} \cdot u$$

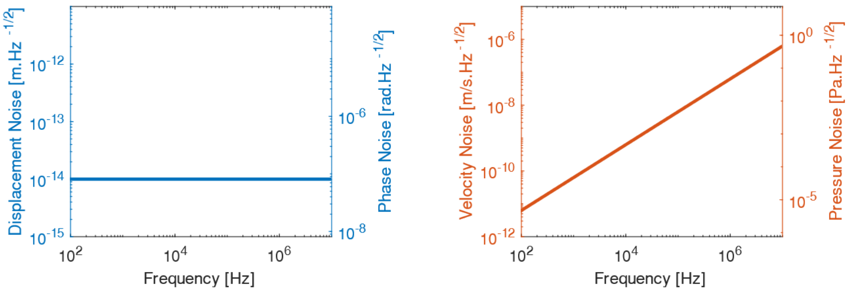

Figure 2 a) Flat displacement and phase noise spectrum for LDV due to shot noise, assuming a 10 mW probing beam and 1% collection efficiency. b) The subsequent pressure noise can be calculated by multiplying the velocity noise by the specific acoustic impedance (1.5 MRayl for tissue)

Silicon photonics-based LDVs for non-contact Photoacoustics

In figure 3, we propose a compact non-contact photoacoustic system for imaging vascularization, using the silicon photonics-based LDV technology described in the previous section.

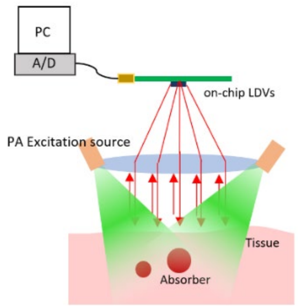

Figure 3 A schematic demonstrating a compact and non-contact biomedical photoacoustic imaging system using silicon photonics based LDVs connected to a digitizer (A/D) and signals are saved and processed into a PC.

The benefits of a system using on-chip LDVs can be clear. First of all, the non-contact nature is desirable in many biomedical applications to mitigate any risks or discomforts from contact methods [4]. Secondly, the on-chip implementation of this system allows for a compact detector system, even for multi-point vibrometers. Combining this with a compact excitation source allows for a completely non-contact compact photoacoustic system [9]. On the other hand, the contactless approach mitigates any interference between the detector to the ultrasound waves and allows for delivering the excitation light directly underneath the probe beams.

The conventional detectors (piezoelectric transducers,..) in contact generally have a better noise floor compared to LDV, but are not suitable for remote detection due to the 1000-fold reduction of the signal pressure due to the impedance mismatch between air and tissue [3] and the very poor transmission of ultrasound frequencies (>MHz) in the air [10]. Optical detection techniques seem more promising for remote detection. However, wideband detection with laser doppler vibrometers results in poor SNR due to the increasing pressure noise floor with the frequency. It is therefore important to consider the application requirements of the detector bandwidth and look at the expected signal strength. Considering a 0.01 $\frac{pm}{\sqrt{Hz}}$ noise limit LDV, a system with a bandwidth from 0 to 2 MHz results in a total noise of around 150 Pa of noise equivalent pressure (assuming Z=1.5 MRayl). Consider an application for imaging vacularization under the skin, the initial pressure due to a photoacoustic excitation can be estimated. For short laser excitations (<10 ns for tissue), one can assume we are in the stress and thermal confinement region. Now, initial pressures can be estimated by multiplying the Grüneisen parameter and the pulse energy [2]. For 10 $\frac{mJ}{cm^2}$ pulses (below the safety limit for NIR light), and considering all light perpendicularly incident on the skin, the initial pressures are in Pa to kPa range for 0 to 5 mm depths. Comparing this to the noise equivalent pressure (NEP) of the LDV, it can be seen that often averaging will be necessary to detect blood vessels at larger depths. Decreasing the LDV bandwidth decreases the noise, but the bandwidth determines the fundamental resolution limit for acoustic resolution photoacoustic microscopy (AR-PAM). A 0 to 2 MHz acoustic detector results in a resolution of around 0.6 mm [1]. Based on these results, it can be seen that LDV can be a suitable detector solution for limited resolution AR-PAM.

Conclusion

Silicon photonics-based LDVs have been proposed as a non-contact detector solution for photoacoustic imaging and sensing. Theoretical limits of LDV noise were calculated and translated into a pressure noise spectrum. The noise of an LDV system with 2 MHz bandwidth was compared with typical photoacoustic-induced pressures and the benefits and drawbacks of on-chip LDV as a detector solution were discussed. From the calculations, it is clear that LDV is a potential detector solution for building contactless and compact photoacoustic sensing or imaging system within the constraints of limiting system bandwidth to limit LDV noise.

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