Speckle mitigation in laser Doppler vibrometry based on a compact silicon photonics chip

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Abstract: A compact six-beam homodyne laser Doppler vibrometry (LDV) system is realized based on a silicon-on-insulator (SOI) photonic integrated circuit. We demonstrate a speckle mitigation method by averaging signals from the six channels.

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1. Introduction

Laser Doppler vibrometry (LDV) is an important technique for displacement or vibration measurements, down to sub-nanometer resolution. Therefore this technique is being used in many application fields [1-2]. Silicon-on-insulator (SOI) photonic technology can be used for the LDV system miniaturization by integrating the LDV-function in a compact photonic integrated circuit (PIC) [3]. It also leads to considerable cost reductions, thanks to the CMOS compatible fabrication process. In this paper, a six-beam LDV-system fabricated on imec's silicon photonics platform through Europractice [4] has been used.

Speckle noise is a major performance-limiting problem in LDV nowadays. It occurs when the vibrating surface has a significant in-plane movement during the measurement. Such movements lead to varying interference conditions for the coupling of reflections from an optically-rough or structured surface (such as a retroreflector) into a single-mode waveguide or fiber. This leads to a low signal to noise ratio (SNR) in the LDV outputs, especially when the interference happens to be destructive. Therefore, demodulated signals are prone to have unexpected steps when such destructive interference events happen, which can be interpreted as pseudo movements. To avoid the bad impact of speckle noise, we propose a speckle-mitigation method by using a multi-beam homodyne LDV, as described hereafter.

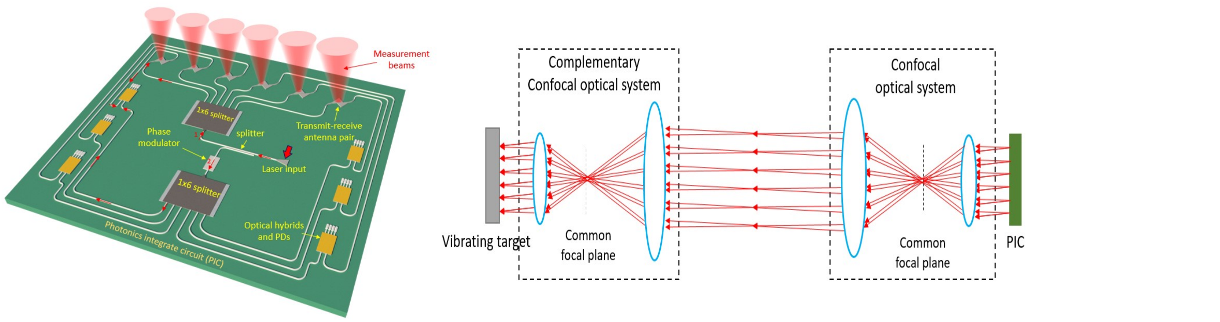

Fig. 1. (a) Schematic show of the external confocal optical system, the six-beam LDV on an SOI-based photonics integrate circuit (PIC). (b) Schematic show of the system used in the de-speckle experiments. The dimensions of the lenses in the drawing are exaggerated to make the design easier to understand.

The proposed PIC with six LDVs is shown in Fig. 1(a). A laser beam (linewidth = 800 kHz, wavelength = 1550 nm) is delivered to the PIC via a surface grating coupler. A directional coupler splits the light power in such a way that around 80% of optical power goes to the measurement waveguide and the rest goes to the reference waveguide. The optical signal in the measurement waveguide is evenly split into six signals via one 1x6 splitter and six transmitting antennas (TAs), spaced by 300 µm, and are then coupled out to the vibrating target. The six measurement beams have to be close enough at the vibrating surface to ensure they are measuring the same displacement. Furthermore the beams should hit the target under normal incidence. For those reasons we use a telecentric optical imaging system with magnification 1 as shown in fig. 1(b),The reflected beams pass through the same optical system and are collected in six receiving antennas sitting next to the corresponding transmitting antennas. The six received signals are then combined with six reference signals (generated by another 1x6 splitter) at six 90-degree optical hybrids, each of which have four outputs connected to four germanium photo-diodes (PDs), integrated on the silicon photonics PIC. Thanks to the 90-degree optical hybrids, the four photocurrent signals for each channel are in quadrature, written as $r\cdot\sin[\theta(t)]$, $-r\cdot\sin[\theta(t)]$, $r\cdot\cos[\theta(t)]$, $-r\cdot\cos[\theta(t)]$, where $\theta(t)$ represents the phase change of the beam that has reflected off the target, which is directly proportional to the displacement, and r is proportional to the amplitude of the useful reflection from the target. After differential amplifiers, two signals in quadrature are obtained, i.e. I ($\propto 2r\cdot\cos[\theta(t)]$) and Q ($\propto 2r\cdot\sin[\theta(t)]$) signals, which are then sent to a decoder for the signal recovery. The most common recovery algorithm is to calculate arctan(Q/I) value, which is also described in [3]. Six displacement signals are finally calculated with this arctan method.

To remove the impact of speckles, the averaging method can be done to the six groups of IQ signals (i.e. obtain the averaged sin and averaged cos respectively before the arctan demodulation) or to the six displacement signals. We propose to use the IQ averaging, since it is proved to be superior in the following experiments.

2. Setup and measurement

In the experiments, the measurement target is a loudspeaker with a large piece of retro-reflector attached to the surface. The target is vibrating at 120 Hz. The six outputs are captured simultaneously at 100 ksps with a DAQ (USB-6353). All the averaging was done by post-processing in a computer.

The six demodulated signals and their SNRs are shown in Fig. 2(a). It is seen that signal 1 and signal 3 have low SNR values (< 7 dB) due to pseudo movements, while the other channels show better SNR values (> 10 dB). We use the channel with the best SNR value as the benchmark (signal 4), which should have almost no pseudo movements. The benchmark signal, the IQ-averaged signal and the displacement-averaged signals are plotted in Fig. 2(b). The figure shows that the IQ-averaged signal is very close to the benchmark, and it is better than the displacement-averaged signals. This is because pseudo movements correspond to relatively low amplitudes in the IQ signals (i.e. r is small for pseudo movement). Therefore, their contributions to the IQ-averaged signal are relatively weak. This is not the case for the displacement-averaged signal, where all channels have the same weight in the final averaged output. The displacement-averaging can be improved by using the diversity combining method [5], but that method is more complicated than the IQ-averaging method. The IQ-averaging can be done simply by connecting the corresponding PDs (e.g. the $r\cdot\sin[\theta(t)]$ signals) of all channels in parallel.

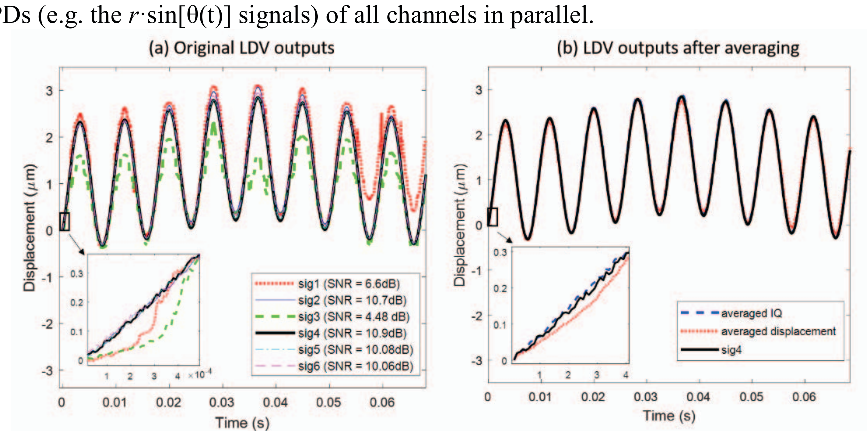

Fig. 2. The averaging effect of six signals: (a) six demodulated signals in which channel 1 and channel 3 show strong deviations due to speckle. (b) Comparisons of the best demodulated signal (channel 4), IQ-averaged signals and displacement-averaged signals.

In this paper, a speckle mitigation method based on IQ-averaging in a multi-channel homodyne LDV is demonstrated. We acknowledge the European Horizon 2020 project CARDIS (Project 644798) for financial support.

4. References

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