Multi-channel laser Doppler vibrometers integrated on silicon-on-insulator (SOI)

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Abstract

Multi-location velocity measurements of a vibrating surface are of interest recently. By scanning the laser beam of a single-point laser Doppler vibrometer (LDV) across the surface of interest, one can realize the multi-location vibration measurement. However, the recovered velocity values of different locations are not obtained at the same time. In many applications, such as measuring the aortic pulse wave velocity, simultaneous velocity measurements for different locations are required. Multi-channel LDVs can be used in this case, in which multiple laser beams are generated and sent to the surface of interest simultaneously. However, the complexity of realizing the multiple interferometers in a bulk LDV system will increase as the number of channels increases, and thus it is very hard to realize a bulk LDV with many channels

We propose to use the silicon-on-insulator (SOI) chip as a platform of the multi-channel interferometers. With the help of silicon photonics and CMOS technology, multiple interferometers can be miniaturized and fabricated on SOI chips. Laser beams are sent into or out of the chip through optimized on-chip grating couplers, with the coupling insertion loss of less than 2 dB per coupler. The total footprint of the integrated multiple interferometers can be very small (several square of millimetres) compared to a bulk LDV system. The cost of the chips will be dramatically decreased for mass production. Additionally, the stability of the integrated interferometers is much better than that of the interferometer built with discrete optical components.

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Introduction

Laser Doppler vibrometers (LDVs) have been widely used in scientific research and industrial applications to conduct noncontact and precise velocity measurements for vibrating surfaces. Most LDVs systems are designed for single point vibration measurements. In some applications, multi-point vibration measurements are required to obtain the velocity distributions. One example is the measurement of aortic pulse wave velocity (PWV), in which vibrations of at least two points on top of the blood vessel should be measured to recover the PWV. If no simultaneous measurement is required, multi-point measurements can be realized by scanning the laser beam of a single-point LDV across the surface of interest. However, for applications that requires strict simultaneous velocity measurements, one need to use multiple LDVs to fulfill this purpose. In bulk optical interferometer systems, realizing such a multi-channel LDV is a complicated work. A lot of work has been done to solve this problem. In [1], two acousto-optic modulators (AOMs) with different frequency shifts were used for both beam splitting and frequency shifting. By intersecting the multiple diffraction orders generated by the AOMs, multiple measuring volumes were formed. In [2], three AOMs were used to generate a 2x5 beam array. However, these reported systems are not compact, and they require using several AOMs, which are power hungry devices.

In this paper, we propose a miniaturized multi-channel LDV integrated on the silicon-on-insulator (SOI), which is fabricated using CMOS compatible technologies [3,4]. The SOI based devices have very compact footprints. The cross section of a single mode rib waveguide on SOI is schematically shown in Figure 1. The typical propagation loss of the guided mode in the rib waveguide is 2.7 dB/cm, and the bend loss for 2 μm radius is 0.039 ±dB/90°[5]. The small bends of the rib waveguides ensures the small footprints of the SOI devices. Due to their compact sizes, the fabrication cost and power consumption of SOI based photonic systems can be dramatically lower than their corresponding bulk optical systems. This is one of the main advantages of the SOI platform.

SOI is also a platform with a lot of high quality building blocks. Grating couplers with the fiber-to-chip coupling efficiency better than -1.6 dB have been reported [6]. They can also be used to couple light between the chip and free space with or without the help of an external lens system. Many other basic components have also been successfully reported, such as fast Germanium photo-detectors [7], carrier injection/depletion based phase modulators [8,9], and FP laser integrated on SOI [10]. Thanks to the realization of these basic components, the SOI platform can be used to design many complex optical systems.

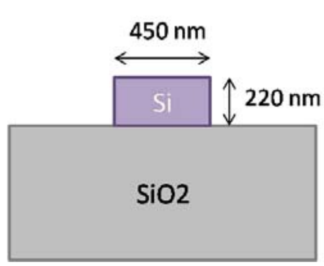

Figure 1. Cross section of a rib waveguide on silicon-on-insulator (SOI).

In the following part, we will demonstrate the realization of a single-point LDV on SOI, and then propose a design on the multi-channel LDVs on SOI. The design and a measurement result of a thermo-optic (TO) based single-point LDV on SOI is going to be discussed in the following section.

Single point LDV on SOI

The optical part of an LDV system is normally a Michelson type or a Mach-Zehnder type of interferometer. In figure 2, a Mach-Zehnder type LDV on SOI is schematically shown. In order to easily demodulate the received measurement signals and retrieve their instantaneous phase information, most LDVs employ the heterodyne detection. In the heterodyne method, light with an optical frequency f_0 is generated from the laser and is split into two parts by an optical splitter. One part of the light, with its amplitude expressed as A, is sent out of the chip via a sending grating coupler and then focused on the vibrating surface under test. We call it the measurement light. The measurement light is scattered by the vibrating surface, and a portion of the backscattered signal is captured by the receiving grating coupler on the chip. (Note that in figure 2, the sending grating coupler and the receiving grating coupler are the same.) Thanks to the Doppler effect, the recaptured measurement signal carriers the velocity information of the vibrating surface in terms of the instantaneous frequency shift (or phase shift). The recaptured signal can be written as $\alpha A e^{j[2\pi f_0 t+\theta(t)]}$, where α is the amplitude loss and $\theta(t)$ is the optical phase change of the recaptured light due to the Doppler effect. The other part of the light from the splitter (the reference light) is sent to the reference arm and undergoes a constant frequency shift f_{OFS} with the help of an optical frequency shifter (OFS). After the frequency shifting, the reference signal is expressed as $Be^{j2\pi(f_0+f_{OFS})t}$. Since the photo-detector (PD) senses the intensity of the combined signal, the photo-current signal can be written as

$$\begin{aligned} I \; &\propto \left|\alpha A e^{j[2\pi f_0 t+\theta(t)]} + Be^{j2\pi(f_0+f_{OFS})t}\right|^2 \\ &= \alpha^2 A^2 + B^2 + 2\alpha AB\cos(2\pi f_{OFS}t - \theta(t)). \end{aligned} \tag{1}$$

It is seen that the photo-current is a frequency modulated signal with a carrier frequency f_{OFS}. The phase shift $\theta(t)$ can be demodulated using an FM demodulation technique. Thanks to this carrier frequency, the useful information $\theta(t)$ is shifted away from low frequency noises, and it can thus avoid many demodulation problems. In this method, the carrier frequency f_{OFS} should be larger than $2(f_v + f_m)$ to avoid problems with the demodulation, where f_v is the maximal frequency of the vibration and f_m is the maximal Doppler frequency shift introduced by the vibration. As a result, the carrier frequency f_{OFS} is usually chosen to be a high value.

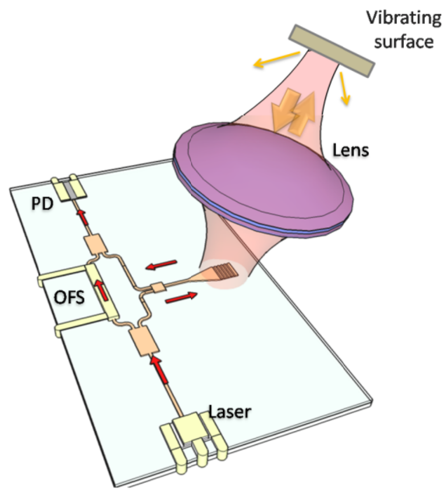

Figure 2. A schematic show of a Mach-Zehnder type LDV integrated on SOI chip.

The most commonly used optical frequency shifters are the AOMs. However, it is difficult to fabricate an AOM on SOI since the piezoelectric effect is absent from unstrained crystalline silicon[11]. We have recently reported a thermo-optic (TO) phase modulation based serrodyne frequency shift, which can generate a frequency shift of several hertz [12].

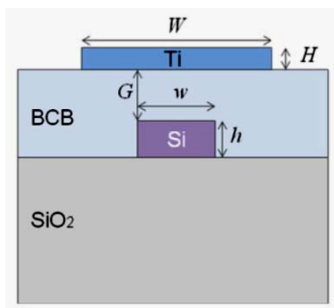

Figure 3. Cross section of a thermo-optic modulator on SOI. Reproduced from[12]**.**

The cross section of the TO phase modulator is shown in figure 3. Using the thermo-optic effect, the Titanium heater is used to modulate the effective index of the silicon waveguide, which can thus modulate the total phase change of the guided mode in modulator region. In serrodyne frequency shift technique, the total phase change should form a specific sawtooth profile. The peak-to-peak value of the phase change should be $N \cdot 2\pi$, where N is an integral. It means that the voltage signal driving the heater should have a square-root-of-time profile [12].

A Michelson type LDV on SOI using the TO serrodyne OFS has been tested. The top view of the design is shown in figure 4. In the Michelson type LDV, a 2x2 multimode interferometer is used for both splitting and combining. Both the measurement light and the reference light are sent back to the waveguides where they come from. Combined light is obtained from the left-up port shown in figure 4. Normally, the backscattered measurement light captured by a Michelson type LDV is stronger than that received by the Mach-Zehnder type. However, more spurious reflections can occur in the Michelson type LDV compared to the Mach-Zehnder type, which can deteriorate the demodulation and result in a deformation in the output.

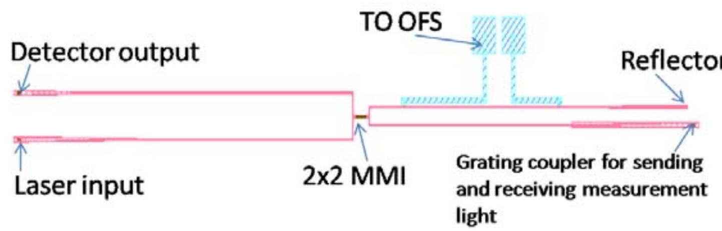

Figure 4. Michelson type LDV using the TO serrodyne OFS.

In this measurement, the f_{OFS} is set 2 kilohertz. A mirror on top of a piezo stacks was used to reflect the measurement signal into the LDV. A vibrating was measured twice by a TO LDV on SOI and a commercialized LDV from Polytec. The time-displacement relation curves for both measurements are plotted in figure 5. It is find that for this vibration, the on-chip LDV almost give the same results as the commercialized equipment. In this measurement, f_v is 22.6 Hz, and f_m is around 50 Hz. However, due to the low optical frequency shift, the measurable vibration is limited. More results on the TO based serrodyne LDV will be published in the future.

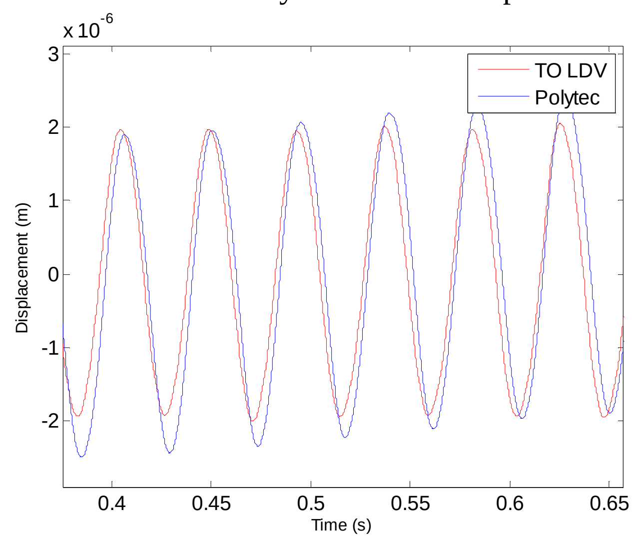

Figure 5. Comparison between the TO LDV (red) and Polytec LDV(blue).

In order to obtain higher OFS on SOI, one can use the carrier injection/depletion based phase modulators. In that case, a relatively large frequency shift can be obtained.

Multi-channel LDV on SOI

For multi-channel LDV on SOI, we propose to use one laser source and one shared OFS for all LDV channels. The shared OFS can be an integrated serrodyne OFS or an external AOM. The Mach-Zehnder type LDV is suggested, because a multi-channel LDV in Michelson type is more complex to design. The array of measurement light can be directly sent out to the free space or sent to a fiber array. The proposed configuration is shown in Figure 6.

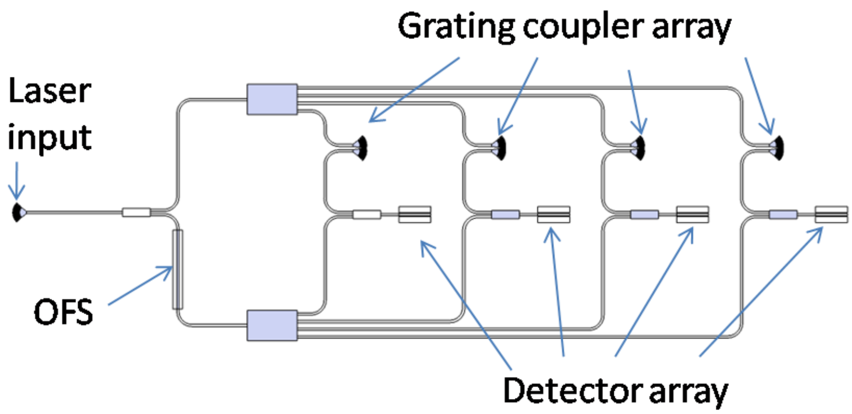

Figure 6. Schematically demonstration of a multi-channel LDV.

The grating coupler array can be designed to have the same pitch of a fiber array. With a fiber array, the measured positions are reconfigurable and the measurement setup is more flexible. A fiber array normally has a pitch of 127 micron. If the device size is only limited by the fiber array, a device with 10 LDV channels will only cover a length of around 1.5 mm.

Sometimes, however, cross talks can happen for adjacent grating couplers. In order to solve this problem, one or several extra OFSs can be introduced to provide different frequency shifts for different channels. In this way, the channels will work at different carrier frequencies, and they will not interference with each other.

Acknowledgements

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