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Miniaturized laser Doppler velocimeters (LDVs) integrated on silicon-on-insulator (SOI)

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Recent developments of micro-photonics make it possible to integrate laser Doppler velocimeter (LDV) systems on chips. We propose a design that an ultra-compact LDV system is built on SOI (silicon on insulator) wafers using low cost CMOS techniques. In this system, the laser diodes and photo diodes can be integrated onto SOI wafers through a BCB (benzocyclobutene) bonding, the Mach-Zehnder interferometer (MZI) can be fulfilled through a passive waveguide design, and the optical frequency shifter which is necessary for most LDV systems, can be realized by a silicon optical phase modulator based on the plasma dispersion effect.

Introductions

Laser Doppler velocimetry (LDV) is a non-contact velocity measurement technique for moving targets (e.g. ear drum or tracer particles suspended in a flow [1]) utilizing the Doppler effect of lasers. It has drawn much attention in various fields, such as the aerospace [2], acoustics [3], and medicine[4]. Commercialized bulk LDVs are available nowadays. But they are still relatively large in size, expensive and power thirsty. The development of silicon-based nanophotonics makes it possible to miniaturize the volume of LDV systems, integrate the optics and electronics on one chip, and reduce their manufacturing cost. In this letter, the authors will present the key components in an LDV system and available means to realize their counterparts in the miniaturized optical circuits.

LDV systems

A typical LDV system comprises an optical and an electrical part. The functions of the optical part include generating lasers, sending/receiving measurement light, and photo-detecting optical signals, while in the electrical part the photo-detected signals are demodulated to recover the target's instantaneous velocities. In this letter, we will focus on the optical part, which will be miniaturized into an integrated circuit (IC) like electronic ICs with our proposed techniques.

Three key components are needed in the optical part: a laser source, a detector, and an interferometer. The configuration of a bulk LDV is represented in Figure 1. A coherent radiation from a laser source is sent to the interferometer, where it is split into two parts by an optical beam splitter: a measurement beam which is sent out to the moving target for measurement, and a reference beam which is used as an optical local oscillator. At the combiner, the frequency modulated measurement beam scattered back by the moving target, is mixed with the reference beam, and the mixed signal is detected by a photo-detector. The time-variant frequency of the photo-detected electrical signal reveal the

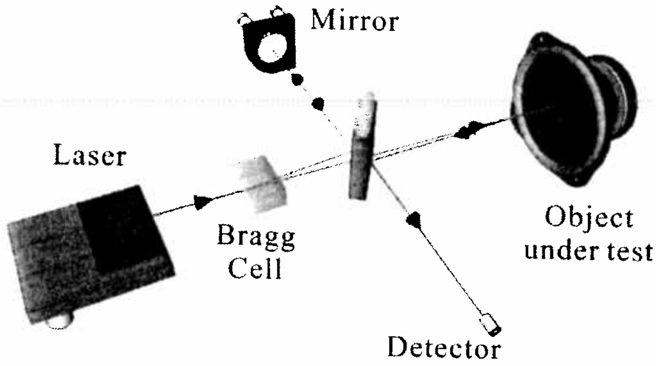

Figure 1: Illustration of a typical bulk LDV system with a heterodyne interferometer. A Bragg cell is used as the frequency shifter.

instantaneous velocities of the target, and their relationship can be approximated by Eq. 1,

$$f_B = f_0 \cdot \frac{2v\cos\theta}{c}, \tag{1}$$

where f_0 is the frequency of the radiation from the laser source, $v\cos\theta$ is the component of the target's velocity along the direction to the receiver, and c is the speed of light in the medium. With the aforementioned relation and the photo-detected signal, the component of the target's velocity is deduced. The electrical part is responsible for the function of recovering (or demodulating) the velocity information.
Homodyne and heterodyne are two basic detection methods of LDV systems. In homodyne the reference beam keeps its original frequency, while in heterodyne its frequency is purposely shifted to provide: 1. a better signal to noise ratio (SNR) compared with homodyne; 2. and the sensitivity of the velocity directions which is normally not provided in homodyne. Thus, LDVs with heterodyne systems are used more widely than those with homodyne. The one illustrated in Figure 1 is a typical heterodyne system, and a Bragg cell is used here as the frequency shifter, which increases or decreases the frequency of the reference beam by a certain amount (e.g. 40 MHz).

Integrated LDV systems on SOI

Silicon-based nanophotonic ICs tremendously increase the integration scale and the functionality per chip, compared with their counterparts in other material systems (glass, III-V semiconductor, etc.) [5]. With the standard complementary metal oxide semiconductor (CMOS) technology, their yield, reliability and economy of scale have been greatly improved [6]. Nanophotonic ICs with low manufacturing cost is possible today. In addition, the developments of indirect bonding techniques, which enable active devices to be integrated on silicon-on-insulator (SOI) substrate, have turned the SOI into a platform for integrating different kinds of nanophotonic components. The aforementioned three basic optical components in an LDV system can be realized on this platform.

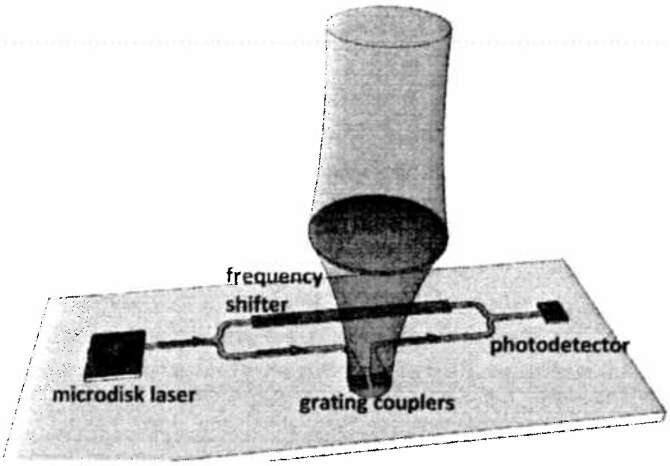

Figure 2: The optical part of the miniaturized laser Doppler velocimetry on SOI with heterodyne interferometer.

In the SOI-based planer lightwave circuits (PLCs), lightwaves can be guided in a rib waveguide, split or combined by a multimode interference device (MMI), and sent out of the PLC through a grating coupler. More complicated passive devices, e.g. Mach-Zehnder interferometers (MZI) and Michelson interferometers (MI), are the combinations of these basic components. These passive components and devices, can be realized on SOI as certain patterns etched into the device layer (top 200 nm silicon layer of SOI) using photolithography technology. The compact size and high precision for SOI-based devices are promised by the high confinement factor of the lightwave in waveguides and the high optical resolution of the photolithography.

Direct fabrications of active components on SOI are not practicable. The active components, however, can be integrated on SOI ICs through an indirect bonding with an intermediate layer of Benzocyclobutene (BCB) [6]. With the bonding technology, our group have reported several successful heterogenous structures on the SOI platform. J. Van Campenhout et al. [7] reported an electrically pumped InP-based microdisk lasers bonded on SOI, with a maximum unidirectional output power of 10 μW, and Joost Brouckaert et al. [8] reported an InAlA-InGaAs metal-semiconductor-metal photodetectors bonded on SOI.

Serrodyne modulation realizes single side-band optical frequency shifts by driving an optical phase modulator with a sawtooth signal, which makes the phase shifts have a peak-to-peak value of $2n\pi$ ($n \in N$). On SOI, one method to fabricate optical phase modulators is to use the thermo-optic effect of silicon. However, due to the limits of heat dissipation speed and power consumption, thermo-optic phase modulators are only used for low optical frequency (<100 kHz) shifts. Another choice is the the plasma dispersion effect [9], with which optical phase modulators on silicon have obtained the cutoff frequency of up to tens of GHz. So in order to generate high frequency shift (e.g. 40 MHz) on SOI, the plasma-dispersion phase shifter with serrodyne modulations can be used.

The final photonic chip that we want to fabricate is illustrated in Figure 2. This photonic chip is going to be integrated with another electronic chip, where the photo-detected signals is finally demodulated.

Discussions and conclusions

Thanks to the developments of silicon-based nanophotonic technology, miniaturized LDV system integrated on SOI is able to implement all the necessary components and functions belongs to the bulk LDV systems. The compact size of the miniaturized LDV system (the footprint of the optical part <1 mm^2) ensures a low power consumption and low manufacturing cost, which makes the miniaturized systems more attractive than the bulk ones. SOI-based nanophotonic IC is a promising technology for the miniaturization of LDV systems.

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