A Novel Optical Waveguide Based Accelerometer

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ABSTRACT

A novel optical waveguide based accelerometer is proposed and modeled. It consists of an integrated laser source, Mach-Zehnder interferometer structure, semiconductor optical amplifier and optical detector on silicon substrate. The acceleration is sensed by the diaphragm structure based on photo-elastic effect. A high level optical integration is achieved in the design.

Key words: accelerometer, MZI, optical integration, photoelastic effect, SOI, electrooptical modulation.

1 INTRODUCTION

Because of the limits of the ICs (Integrated Circuits) and the superior properties of optical devices [1], more and more attentions have been paid to the research on the optical devices and their integration with electronic devices. Nowadays, individual optical devices are commonly known to provide good performance along with high price. The way to lower the price of optical devices naturally leads to the integration [2].

Accelerometers are used in a very wide range of applications, such like earthquake detection, mineral detection, vehicle crash protection systems, medical care and so on. Proper use of accelerometers can keep people out of hazardous working environments. Some key properties of the accelerometer, such as sensitivity, intensity and measurable frequency range etc. are addressed and pursued by researchers. The optical waveguide based accelerometer monolithically integrates the different optical components such as laser diode, optical modulator, optical amplifier, photo detector, etc. Furthermore, electronic components are also integrated with the optical part on the same chip. It has the advantages in the better performance as a sensor due to the compensations from electrical and optical parts. It therefore has the advantages over other implementations [3, 4]. In this paper, we first illustrate the overall structure of the proposed accelerometer system, then we focus on the optical sensor part. Principles of operation of the optical sensor are then illustrated and discussed.

2 ACCELEROMETER SYSTEM

The overall system can be divided into two main parts: optical part and electronic part. Optical sensor part can be decomposed as sensing part and optical processing part. The electronic processing part is made up of analog part and digital part which can be further decomposed as demodulation part and algorithm part. The structure of the system is shown in Figure 1.

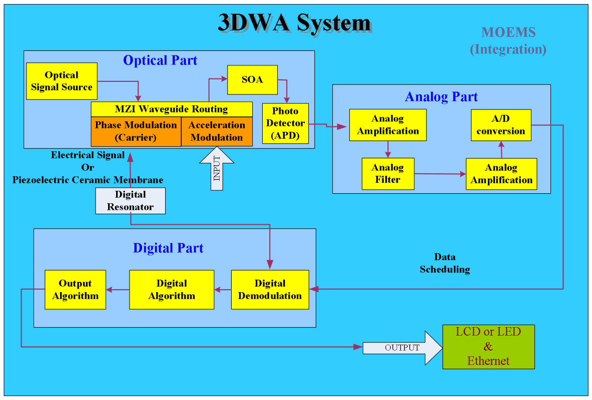

Figure 1 Overall structure of accelerometer system

From Figure1 we can see the individual parts do not only communicate with each other within the same domain but also different parts from different domains interact each with the other (e.g. optical and digital parts). The input of the system is acceleration signal which is presented as mechanical vibration. This vibration is sensed and converted into optical form (phase of the light). The light, where the signals are on, is emitted by an integrated light source. After being processed in optical part, such as amplification, the light signal that contains acceleration signal is output into electrical form by transformation in a photo detector. The electrical signal is further fed to analog part and digital part for signal processing. Weak signals are amplified and noise contained is filtered by analog amplifier and filter in analog part. The acceleration signal is demodulated out in demodulation block. The demodulated signal is further processed in the algorithm block. At last, we are getting electrical signal at the output of the system. This signal is presented in either analog or digital form. The overall system is realized by using silicon substrate due to the advantageous properties of the silicon and its fabrication process.

3 OPTICAL SENSOR

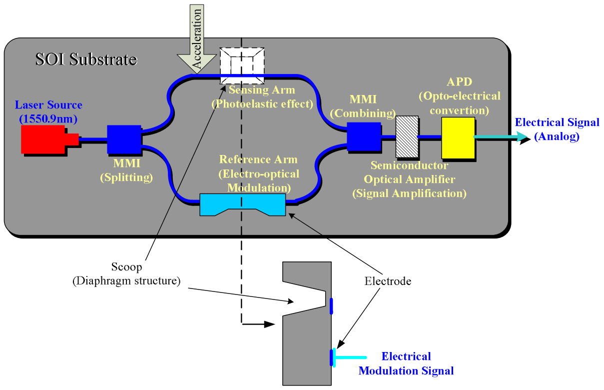

Figure 2 Structural optical sensor

As shown in the Figure 2, on a SOI (Silicon on Insulator) substrate, the light with wavelength 1550.9 nm is emitted from the integrated laser source as the information signal carrier. The light from laser is then split into two identical waves with same amplitude and phase by an MMI (MultiMode Interferometer) which is used as a splitter [5]. One wave propagates along the sensing arm where incoming acceleration is sensed by photo-elastic effect. The other wave propagates along the reference arm, where a reference signal is added by electro-optical effect. Both the acceleration information and reference signals are carried in the phase part of the light. Then the two waves are recombined by MMI which is used as a combiner. Due to the properties of the Mach-Zehnder Interferometer (MZI), the signal contained in the phase part is then indicated in the form of amplitude [6]. Because of the existence of the optical loss, a Semiconductor Optical Amplifier (SOA) is placed right after the point where light exits the combiner to amplify the weak signals. After the photo detector (APD is used here to boost the signal again), the optical signal is transformed into electrical form which is proportional to the intensity of the light.

As can be seen from above, the optical sensor consists of a series of individual optical devices: Laser Source, MZI Modulator, SOA and APD. The devices are individually designed first, and then they are bonded to the SOI substrate. We will next introduce the individual devices as well as their bonding.

3.1 Waveguide Structure

Before we go to details of each component, we first look into the waveguide structure which is the most fundamental element. Rib-SOI structure is adopted as shown in Figure 3, to guarantee a low loss waveguide, light propagation mode in the waveguide is best to be single mode [7]. It satisfies

$$\frac{W}{H} \le \alpha + \frac{h/H}{\sqrt{1-\left(h/H\right)^2}} \qquad (1)$$

where W is the width of the ridge, H is the total height of the ridge area, h is the slab height, α is a constant with value of 0.3. Based on (1), we calculated the parameters of the waveguide and simulated by OptiwaveBPM for 3D case. We get the signal-mode distribution as shown in Figure 4.

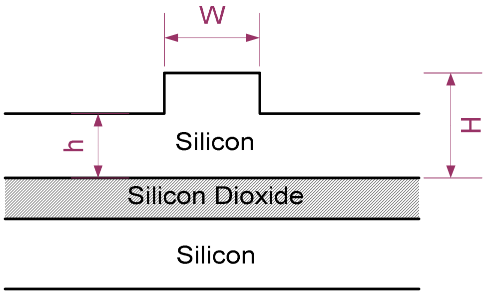

Figure 3 The cross section show of the Rib-SOI

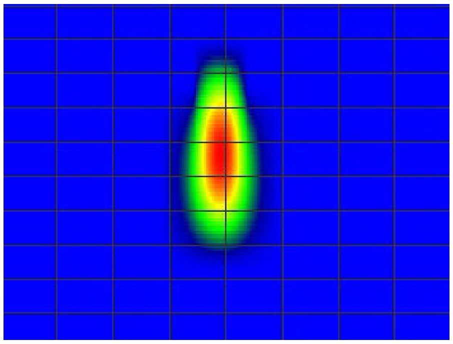

Figure 4 Mode distribution in waveguide

3.2 Laser Source

Based on [8], we could implement the light source by using III-V materials on silicon substrate. The electrons are emitted from a semiconductor or metal surface, through an insulator layer, and are injected into a layer of optoelectronic material placed on the insulator layer. One of the possible methods for silicon integration is shown in Figure 5.

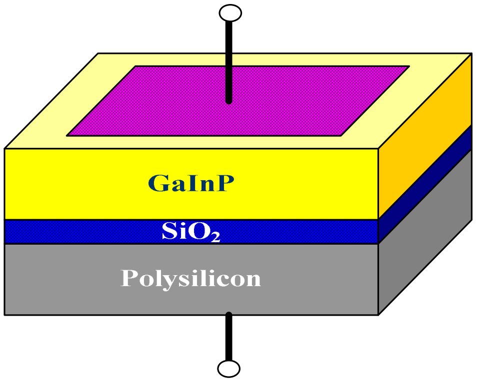

Figure 5 The silicon-base integration structure for LD

For SOI substrate, we can first remove the silicon on top of the SiO2, etch part of the SiO2 to reduce the width of the oxide layer to tens of nanometers according to the invention. Then the light source material, say GaInP, is sputtered on the silicon dioxide layer. It needs not to be single crystal. When the electrodes are applied on both sides, the electrons are emitted from the silicon layer and injected to the GaInP layer through the insulator layer which is SiO2. Getting the electrons from underneath, GaInP layer would be exited and emit light. Therefore, an integrated laser source on silicon could be realized by this method.

3.3 MZI Modulator

By photo-elastic effect [9, 10] and electro-optical effect [11, 12], the light signal is continuously modulated.

Photoelastic Modulation

For SOI wafer, there is a thick layer of silicon under the SiO2 layer. Some hollow cubic regions can be etched in this layer to form the diaphragm structure with a very thin membrane surrounded by the thick silicon. It’s just like we scoop out some silicon in the bulk silicon. The sensing waveguide is laid on the top of the diaphragm. When the acceleration is coming, diaphragm region with thin thickness vibrates according to the acceleration while rest of the part stays still or has negligible vibrations. This is caused by the sensitive differences among different thickness. According to the photo-elastic effect, the vibration varies the polarization state of the propagating light and certain phase variation is then introduced to propagating light as can be seen in (2).

$$|\Delta\phi| = \frac{2\pi dk}{\lambda}\frac{F}{S} \qquad (2)$$

where d is the thickness of the membrane, k is the photo-elastic constant, λ is the wavelength of the light, S is the area of the membrane, F is the applied force.

The length to width ratio of the membrane should be larger than 2 [13]. The sensing waveguide should be laid on the long edge of the diaphragm as shown in Figure 6. There are three scoops under sensing arm which helps to improve the sensitivity of the devices.

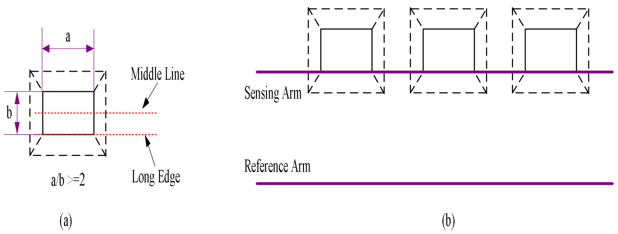

Figure 6. The structure of sensing diaphragm (a) and sensing arm (b)

Electrooptical Modulation

Because of the weak electro-optical modulation effect silicon has, by doping in certain regions of the SOI-Rib, the modulation scheme could be formed [14]. When the voltage is applied on the electrodes, the propagating light is modulated, as can be seen in Figure 7. This modulation is the result of combination of four effects: Linear Electro-optic Effect (LEO), Electro-refractive Effect (ER), Plasma Effect (PL) and Band-Filling Effect (BF). In our case, the carrier distribution within the material which is PL is the main factor to cause the light modulation. The index changes with PL and therefore the phase changes according to the applied voltage. When the applied voltage, which impacts on electrical field, changes continuously, the refractive index changes continuously, and so the phase of the light changes also continuously. By adopting this scheme, the light is modulated by electrical ways.

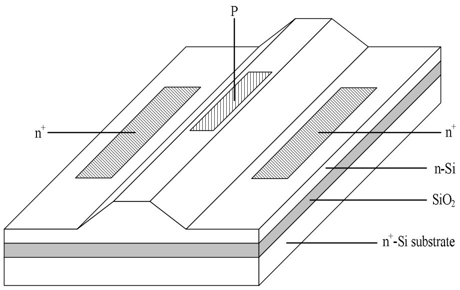

Figure 7 The structure of electro-optical modulation on rib-silicon

3.4 SOA and APD

The SOA is used to amplify the signal intensity. It uses the same principle of laser source. Germanium introduced silicon photo detector which reduces the bandgap and extends the maximum detectable wavelength is used to detect the light with wavelength of 1550.9 nm. By using this principle, the repeated structure of p-n junction is formed and therefore the APD is realized.

5 CONCLUSION

The structure and principles of operation of an optical waveguide based accelerometer are introduced in the paper. MEMS techniques are used for its fabrication to maintain the compact size of the sensor and its good performance. The use of silicon as fundamental material is preferred as it is easy integrate sensing part with the electronic part and the advanced silicon technology can also be used to facilitate the fabrication. Recently, pure silicon based light source is reported [15], which give us confidence that all silicon based accelerometer would be feasible in the near future.

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