Optical Ultrasound Sensor Based on Silicon Photonic MEMS Cantilever with Tunable Dynamic Range

Dong J. Choi[1], Sangwoo Nam[1], Min G. Lim[1], Young J. Park[1], Man J. Her[1], Dong U. Kim[1], Hyojin Seong[1], Sangyoon Han*[,1,2], and Jaesok Yu**[,1,2]

[1]*Department of Robotics Engineering, DGIST, Daegu 42988, Republic of Korea*

[2]*DGIST Robotics Research Center, DGIST, Daegu 42988, Republic of Korea*

**E-mail address: s.han@dgist.ac.kr, **E-mail address: jaesok.yu@dgist.ac.kr*

***Abstract*— We report on an optical ultrasound sensor with the silicon photonic MEMS cantilever. The optical ultrasound sensor operates in the air and its sensitivity and dynamic range can be tunable with applied voltages. The length of our sensor's cantilever is 23 µm and the thickness is 220 nm, respectively. The resonance frequency of the optical ultrasound sensor is 700 kHz and has a maximum sensitivity of 3.39 mV/Pa when the ultrasound signal is 700 kHz**

I. Introduction

Ultrasound sensors have been widely used in various applications such as medical imaging, industrial inspection, and non-destructive testing. Ultrasound sensors usually use piezoelectric ultrasound transducers to convert acoustic pressure energy into electrical signals based on piezoelectric materials. They can detect a wide range of ultrasound frequencies and are widely used. However, the sensitivity and dynamic range of the sensors are fixed and as a result, they can suffer signal saturation or low sensitivities. In addition, the manufacturing of the sensors requires several manual steps which result in high costs.

We introduce a new type of optical ultrasound sensor using silicon photonic waveguides combined with a MEMS cantilever membrane. The optical ultrasound sensor is highly sensitive, and its sensitivity and dynamic range are tunable. Our sensor combines the advantages of both silicon photonics and MEMS to provide a new approach to measuring ultrasound. Silicon photonics uses the light interference effect to precisely measure the location of the MEMS membrane. The sensor consists of a silicon photonics waveguide that is integrated with a cantilever MEMS structure. The MEMS cantilever is designed to be highly sensitive to mechanical vibrations, including ultrasound signals [1][2]. The resonant frequency of the sensor can be adjusted by controlling the dimensions of the cantilever. MEMS and silicon photonic devices are highly compact and can be integrated with other devices on a single chip, making them well-suited for a wide variety of fields and can be fabricated using standard semiconductor fabrication techniques, so they can be manufactured at a relatively low cost.

II. Design and Experiments

Figure 1 is the schematic for the principle of MEMS cantilever structure used in our optical ultrasound sensor. The sensor consists of a pair of two waveguides lying in parallel. One of the waveguides is attached to the cantilever MEMS membrane. Depending on the distance between the two waveguides, the intensity of the light signal changes. When ultrasound vibrates the membrane (Fig. 1), the distance between the waveguides changes, and as a result light signal tracing the ultrasound pressure is generated (Fig. 1(a), (b)). Since the resonance frequency is determined by the length and thickness of the cantilever, the sensor can be designed in that it is more sensitive to a specific frequency. The initial location of the MEMS cantilever can be tuned by applying the voltage to the cantilever. In this way, the dynamic range and the sensitivity of the ultrasound sensor can be adjusted.

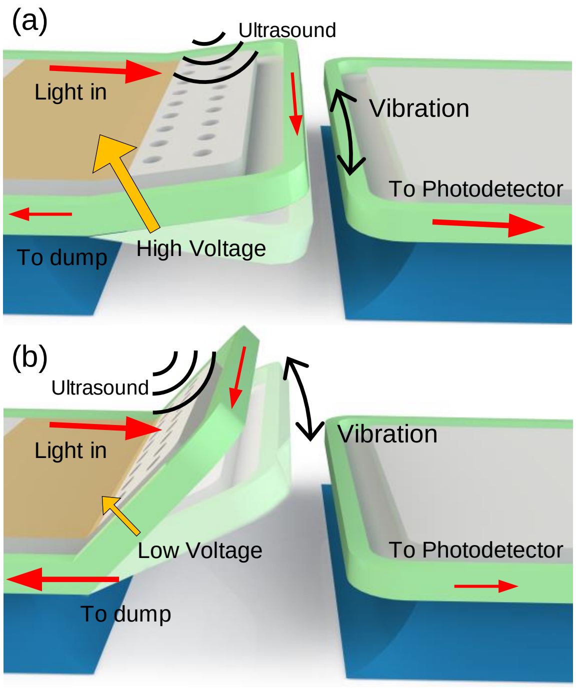

Figure 1. (a) Schematic for the vibration of the cantilever when the ultrasound signal is reached (with high voltage), (b) Schematic for the vibration of the cantilever when the ultrasound signal is reached (with low voltage)

Figure 2(a) is an optical image showing the setup we used to characterize the sensor. The chip operates in the air, and a grating coupler is used to couple a laser and photodetector to the input and output of the waveguide on the chip. The distance between the transducer and the sensor is about 25 mm. A tunable laser with a wavelength near 1550 nm was used to detect the ultrasound signal. A photodetector having 125 MHz bandwidth was used. Figure 2(c) is the SEM image of our optical ultrasound sensor. The MEMS cantilever is designed with a length of 23 µm and a thickness of about 220 nm, respectively. The resonance frequency of the cantilever corresponding to this length and thickness is about 700 kHz. The height of the cantilever beam is determined by applying a voltage corresponding to the range of 0 V to 5 V [3][4]. The dynamic range of the sensor is determined according to the initial height of the cantilever according to the applied voltage, resulting in a difference in sensitivity. Figure 3(a) shows our sensor's measured time-domain received signal measured with a photodetector in response to the transmitted ultrasound signal. The center frequency of the ultrasound signal used in this experiment is 700 kHz. The sensitivity when a 2 V voltage is applied is about 5 times more sensitive than the sensitivity when a 5 V voltage is applied. Figure 3(b) shows the measured frequency-domain received signal of our sensor in response to the transmitted ultrasound signals of different frequencies. The sensor with the specific voltage applied was measured at intervals of 100 kHz from 300 kHz to 1700 kHz. The output of the sensor is the largest at approximately 0.15 V on a 700 kHz ultrasound signal. When an ultrasound signal emitted at 25 mm reaches the chip, its intensity is about 44.24 Pa. The sensitivity of the sensor to the 700 kHz ultrasound signal in the air is 3.39 mV/Pa.

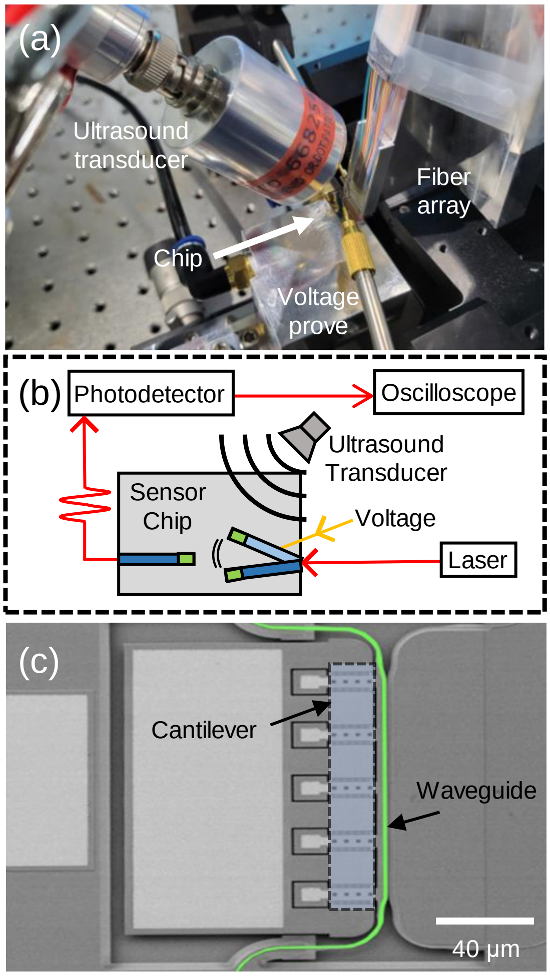

Figure 2. (a) Optical image showing the setup, (b) Schematic diagram corresponding to (a), (c) SEM image of our optical ultrasound sensor.

In summary, we have introduced a new structure for an optical ultrasound sensor that can detect the specific frequency ultrasound and its dynamic range can be tunable by voltage. As the sensor is built on a silicon photonics platform which is similar to the CMOS process, the manufacturing and integration of the sensor can be much simpler than the conventional piezo-based sensors.

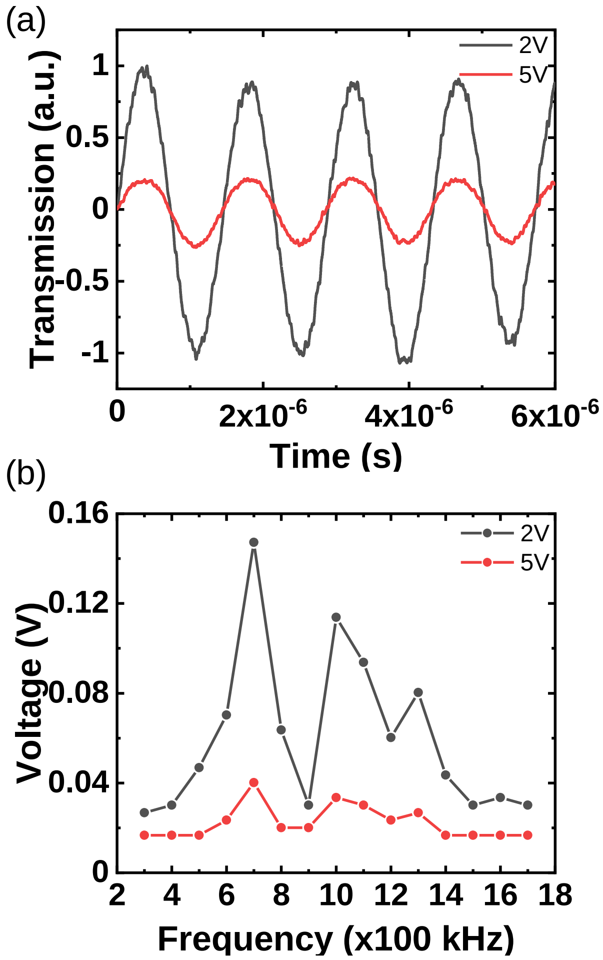

Figure 3. (a) The measured time-domain received signal of our sensor, (b) The measured frequency-domain received signal of our sensor in response to the different frequency ultrasound signals

This work was supported by Samsung Research Funding & Incubation Center of Samsung Electronics under Project Number SRFC-IT2102-02.

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