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An acousto-optic sensor based on resonance grating waveguide structure

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Abstract

This paper presents an acousto-optic (AO) sensor based on resonance grating waveguide structure. The sensor is fabricated using elastic polymer materials to achieve a good sensitivity to ultrasound pressure waves. Ultrasound pressure waves modify the structural parameters of the sensor and result in the optical resonance shift of the sensor. This converts into a light intensity modulation. A commercial ultrasound transducer at 20 MHz is used to characterize a fabricated sensor and detection sensitivity at different optical source wavelength within a resonance spectrum is investigated. Practical use of the sensor at a fixed optical source wavelength is presented. Ultimately, the geometry of the planar sensor structure is suitable for two-dimensional, optical pressure imaging applications such as pressure wave detection and mapping, and ultrasound imaging.

Keywords

acousto-optic; ultrasound sensor; resonance grating waveguide; polymer sensor

I. Introduction

Ultrasound imaging has been widely used in many medical and clinical applications [1-4]. Typical ultrasound imaging has been obtained using piezoelectric-based ultrasound sensors. However, when piezoelectric-based sensors are used as high frequency 2D imaging arrays, many challenges need to be addressed [3, 5]. These include the fabrication of miniaturized arrayed piezoelectric sensor elements, compact electrical interconnections of individual sensors, electrical cross-talk between arrayed sensors, etc. As an alternative method to address these limitations, optical detections of ultrasound waves have been studied. The basic detection mechanism shares a general concept that ultrasound pressure waves modulate an optical device structure and its acousto-optic response is measured by photodetectors. To enhance the acousto-optic sensitivity, various resonance structures such as Fabry-Perot etalons [6, 7], planar Bragg gratings [8], and micro-ring resonators [9] were

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studied. Among them, Fabry-Perot resonance was widely studied for ultrasound sensing because of its potential for 2D ultrasound imaging capability, good sensitivity, and broadband response. The sensitivity is known to be directly related with the finesse quality of the resonance structure and the Young's modulus of the cavity material. Improving the finesse quality requires multilayered dielectric reflectors. Typically, inorganic dielectric materials are used. However, the precise deposition of multilayered stacks [6] on a flexible material possesses high cost and requires careful control of processing condition and temperature to minimize cracks due to intrinsic material strains.

In this paper, we present an acousto-optic sensor based on a resonance grating waveguide structure. Based on periodic 1D nanostructure, its fabrication eliminates complex multilayered mirror fabrication steps and its resonance peak can be easily modified by changing the period of the nanostructures. Furthermore, the demonstrated structure utilizes polymer-based materials. The low Young's modulus of polymer-based materials compared to that of dielectric materials allows a potential improvement of acousto-optic sensitivity. The geometry of the planar sensor structure is also suitable for two-dimensional, optical pressure imaging applications such as ultrasound imaging and pressure wave detection/mapping. In the following sections, the operation principle of the proposed ultrasound sensor is first discussed. Secondly, the sensor fabrication procedure and measurement are outlined. The static pressure characterization and dynamic ultrasound detection using the fabricated sensor are described. To our knowledge, this represents the first demonstration of ultrasound wave detection using a sensor based on polymer-based resonance grating structure. Finally, the experimental results and practical use of the sensor are discussed.

II. Design and fabrication

A. Principle of Ultrasound Detection

The schematic structure of the acousto-optic sensor developed in this paper is shown in Figure 1(a). This device is based on a resonance waveguide grating structure, which is composed of three polymer layers: a grating layer (Microposit S1805, Shipley Corp), a waveguide layer (NOA 164, Norland Products Inc), and a cladding layer (Sylgard 184 polydimethylsiloxane (PDMS), Dow Corning Inc). Here, we choose PDMS and NOA 164 polymer materials due to their relatively low shore hardness (shore A: 45 and 10 respectively). The utilization of these flexible polymers allows the waveguide grating structure to deform easily when external ultrasound waves are applied on the sensor structure. A rigid glass substrate is used as a supporting substrate for the device structure. In our sensor implementation, the sensor surface is immersed in water, an optical signal is illuminated through the glass substrate and the reflected resonant optical spectrum is used to detect ultrasound signals applied on the surface of the sensor. Figure 1(b) is an example of a reflected spectral response of a fabricated sensor. The resonance peaks in the reflected spectrum have been known to be very sensitive to the dimensions of the sensor [10]. Any changes in the structural parameters lead to shifts in the resonance peaks. This forms the basic sensing mechanism of our device. The schematic transduction mechanism of our sensor is illustrated in Figure 1(c). At a fixed wavelength within a resonance spectrum, a resonance peak shift induces a change in optical intensity corresponding to applied

ultrasound pressure waves. The optical signal is then converted into a voltage signal by a photoreceiver. Considering all these factors, the overall sensitivity (S) of the sensor is expressed with

$$S = \frac{\Delta V}{\Delta P} = \frac{\Delta V}{\Delta I} \frac{\Delta I}{\Delta P}$$

where P is the ultrasound pressure amplitude applied onto the sensor, I is the reflected light intensity from the sensor, and V is the voltage at the output of the photoreceiver.

For a given photoreceiver performance ($\frac{\Delta V}{\Delta I}$), the sensitivity of the sensor is dependent on the light intensity change corresponding to the applied pressure on the surface of the sensor. The sensitivity and dynamic pressure range of the sensor depend on the slope and linear range of the resonant spectrum, respectively. By having a narrow resonant spectrum, it is expected to improve sensor sensitivity while its dynamic pressure range is reduced.

B. Fabrication

The fabrication procedure and an image of a fabricated acousto-optic sensor are shown in Figure 2(a-g). The substrate used is a 1mm thick, $25.4 \times 25.4 \text{ mm}^2$ clear glass. A relatively thick glass is used to prevent the substrate from deforming due to the pressure waves exerted by the ultrasound transducer. The glass is cleaned using a three-step procedure using acetone, methanol, and isopropyl alcohol; and fully dehydrated at 180°C for 15 minutes.

Subsequently, a mixture of Dow Corning Sylard 184 PDMS and curing agent is prepared with weight ratio of 10:1, respectively. The PDMS mixture is degassed in a vacuum chamber until all bubbles are removed. The mixture is then poured on top of the glass substrate, spread at 250 rpm for 5 seconds, and spun at 500 rpm for 30 seconds. This creates a uniform layer of PDMS with a thickness of $140\mu\text{m}$ (Figure 2(a)). The sample is baked at 125°C for 60 minutes to allow the PDMS layer to be fully cured, and then cooled to room temperature. This layer is highly hydrophobic and consequently, treated using oxygen plasma to enhance the adhesion between the PDMS cladding layer and the subsequent waveguide layer.

NOA 164 polymer is spin-coated at 5000 rpm for 30 seconds creating a uniform waveguide layer with a thickness of $1.5\mu\text{m}$ (Figure 2(b)). The sample is immediately exposed under an inert nitrogen atmosphere with 365nm UV light until fully cured. An inert atmosphere is used to reduce oxygen inhibition on the waveguide layer during the curing process. The cured layer is then treated using oxygen plasma to improve the adhesion with the subsequent layer.

Microposit S1805 positive photoresist is spin-coated at 5000rpm on top of the fully-cured NOA 164 and baked at 90°C for 90 seconds. The resulting photoresist thickness is approximately 500nm. The diffraction gratings are fabricated using Lloyd's Mirror Interferometer custom-made setup [11]. The set up consists of a 405nm ultraviolet (UV) diode-pumped 30mW laser, a spatial filter, and a shutter, in conjunction with the

interferometer. Using this setup, the grating period can be changed by adjusting the rotational platform relative to the incident laser beam. This enables the fabrication of grating periods that are tuned for specific resonance peaks. During exposure, samples are placed in a sample holder and the angle of the rotating platform is adjusted accordingly. The shutter is opened and the samples are exposed for a predetermined amount of time (Figure 2(c)). The exposed samples are developed by dipping and lightly agitating them in a solution of Microposit MIF-319 developer, and then rinsed in deionized water. Developing time varies between 5-10 seconds to develop the photoresist appropriately (Figure 2(d)). The resulting grating pattern period is fabricated to about $1\mu\text{m}$ to render a reflective spectrum suitable for the testing setup. The overall device is shown in Figure 2(e), the top view of the resulting grating is shown in Figure 2(f), and a cross sectional picture is given in Figure 2(g).

III. Device Characterizations

In order to evaluate the performance of the sensor, the static characteristics of the sensor at constant pressures are first performed in a sealed air chamber, as shown in Figure 3(a). Pressurized nitrogen air is supplied into the air chamber using a pressure regulator. The applied pressure ranges from 0 kPa to 310 kPa. A broad-band, polarized light is guided to the sensor from the bottom glass substrate. The reflected light from the sensor is collected and analyzed in an optical spectrum analyzer. Figure 3(b) shows the measured resonance shift of the first-order mode peak as a function of the applied pressure. The results demonstrate that the peak gradually shifts to a higher wavelength as the applied pressure is increased. The first-order mode wavelength peak located at $\lambda=1542.6\text{nm}$ effectively shifts 1.0nm to a higher wavelength of 1543.6nm when a pressure of 310kPa is applied on the sensor. This effectively demonstrates a static sensitivity of 3.2pm/kPa . In addition, the performance of the sensor does not change as the applied pressure is increased and decreased successively. This indicates that the sensor has a good repeatability.

Generally, in a resonant waveguide grating structure, as its grating period or waveguide thickness is increased, its resonant peak is shifted to a higher wavelength. It is also observed that the resonant peak splits when the incident beam angle changes from its normal incidence angle to the surface of the structure [10]. Based on our measurement results shown in Figure 3(b), the resonance peak shifts to higher wavelengths as higher pressures are applied on the sensor surface. There is no observed splitting of the peak resonance. This indicates that the dominant sensing mechanism in our structure is the increase of the grating period when pressure is applied on the sensor.

The dynamic characteristics of the sensor are studied using Olympus M316-SU 20MHz immersion transducer (3mm element diameter) in a custom-built leak-proof Teflon reservoir. The sensor is secured to the bottom of the reservoir and the reservoir is filled with deionized water ($n = 1.33$) allowing the gratings to come in direct contact with the DI water. The effective area of the sensor touching the deionized water is 8mm in diameter. Ando AQ8201-13 tunable laser source illuminates the grating from the bottom after passing through a NIR Glan-Thompson polarizer. To maximize the reflective spectrum signal, the polarizer is adjusted so that the light polarization illuminating the sample is parallel to the grating orientation, i.e., it achieves a TE polarized light. NIR mirrors guide the laser source

to the sensor and the reflective spectrum to a collimator. The optical signal is then detected using Wavcrest OE-2 optical-to-electrical converter. The ultrasound transducer operates using JSR Ultrasonics DPR500. The dual pulser/receiver allows transducer control and detection of the resulting echo signals. Both sensor and transducer signals are measured using Tektronix TDS784C oscilloscope. Figure 4 demonstrates a simplified schematic of the overall testing and measuring set up.

IV. Results and Discussion

First, the optical sensor characteristic is measured through a tunable laser range with a wavelength range of 1460nm to 1580nm. The reflective spectrum of the device under DI water is shown in Figure 5 as a function of the laser wavelength. In the fabricated polymer-based device, the grating serves as an optical wavelength filter: the signal is strongly reflected at specific wavelengths. The measured reflective spectrum peaks at 1538.0nm with a FWHM of 0.9nm.

The sensor response is then tested with the 20 MHz piezoelectric transducer. DPR500 pulser is set at 330V for the pulse voltage amplitude and 200 Hz for the repetition rate. The peak pressure from the transducer is calibrated using a polyvinylidene fluoride (PVDF) needle hydrophone (model 80-0.5-4.0, Imotec Messtechnik, Warendorf, Germany). The measured peak-to-peak pressure is 205kPa at the above measurement setting. The tunable laser wavelength is fixed near the peak reflective wavelength. Without the ultrasound input from the transducer, the measured reflected optical signal is constant. When the ultrasound transducer is triggered, ultrasonic pressure waves are generated and press onto the acousto-optic sensor. Figure 6(a) demonstrates the periodic echo signal collected directly from the ultrasound transducer. The first signal peak change results from the DI water-polymer interface in the sensor surface. The stronger second peak is attributed to the signal reflection from the larger acoustic impedance mismatch between the soft polymer and hard glass interface. Lastly, the remaining peaks are due to the lingering resonance between the polymer structures and glass substrate. Coinciding with the echo signal, the generated ultrasonic pressure waves induce a deformation of the layered structural parameters of the sensor. Consequently, this deformation results in shifts of the resonant reflective spectrum. Figure 6(b) shows the sensor response collected when the tunable laser is fixed at 1538.2nm and the ultrasound transducer pulsates at 20MHz. Clearly, the ultrasonic pressure waves effectively modulate the fabricated sensor response. Unlike the echo signal, the first peak has the strongest response in the optical response. This indicates that the grating structure is predominately modulated when the pressure waves transition from the DI water and polymer grating interface. As expected, the first peak exhibits the strongest response, while the subsequent peaks decay exponentially. The measured signal-to-noise ratio (SNR) for the AO sensor at $\lambda=1538.2\text{nm}$ is 32.83dB. This result closely follows the measured SNR for the echo signal by a piezoelectric ultrasound transducer at 32.22dB. Figure 6(c) shows the frequency response of the measured pulse responses for the fabricated AO sensor and the piezoelectric transducer. The -6dB bandwidths of the fabricated AO sensor and the piezoelectric transducer are 25MHz and 19MHz, respectively.

In Figure 7, the overall sensor response is shown as a function of the incident laser wavelength. This demonstrates that the sensor response varies depending on the wavelength in which the incident laser wavelength is fixed. From the sensor characteristic shown in Figure 5, at the bottom of the reflective spectrum ($\lambda=1536.6\text{nm}$), the sensor response is weak. Increasing the wavelength ($\lambda=1537.4\text{nm}$) leads to a stronger signal. At the spectrum peak ($\lambda=1538.0\text{nm}$), the signal weakens. The sensor response then reverses and increases in strength ($\lambda=1538.2\text{nm}$) and weakens again ($\lambda=1538.8\text{nm}$). This indicates that the fabricated sensor sensitivity can be maximized by the wavelength locality selected, i.e., by the overall reflective spectrum power – but more significantly – the gradient or slope of the selected wavelength. The strongest sensor response occurs at $\lambda=1538.2\text{nm}$ and not at the reflective spectrum peak of $\lambda=1538.0\text{nm}$. Additionally, the sensor response reversal is detailed in Figure 7 (b) and (d). The reversal is shown using two different points that have opposite responses, $\lambda=1537.4\text{nm}$ and $\lambda=1538.2\text{nm}$. As demonstrated in Figure 5, these two wavelengths are in opposite sides of the reflective spectrum. At $\lambda=1537.4\text{nm}$, the spectral characteristic demonstrates a positive gradient, whereas at $\lambda=1538.2\text{nm}$, such gradient is negative. In addition, from the results obtained in Figure 7 (a-e), the AO sensor demonstrates a SNR of 17.47dB, 32.84dB, 19.42dB, 30.81dB and 16.84dB for each of the respective wavelengths. Furthermore, the measured sensitivities of the fabricated sensor at different wavelengths are summarized to 1.56 mV/kPa, 9.89mV/kPa, 2.01mV/kPa, 7.98mV/kPa, and 1.42mV/kPa, respectively. This indicates that both, sensor SNR and sensitivity are dependent on the incident laser beam wavelength and can be subject to optimization.

The sensor response delay was investigated by varying the distance between the transducer and the acousto-optic sensor. The transducer is first placed close to the surface of the sensor. Using this as the reference point, the distance is then increased. Figure 8 shows that the device response delay increases as the distance between the acousto-optic sensor and the ultrasound transducer increases. The observed delay time in water is $3.1\mu\text{s}$ for an increased distance change of approximately 10mm. Considering that the pulse response from the sensor is less than $0.1\mu\text{s}$ in this experiment, this effectively demonstrates that the sensor is able to resolve thin structures as small as $300\mu\text{m}$ in ultrasound imaging applications.

In a practical application, the sensor resonance peak needs to be aligned with the wavelength of the laser source. While the sensor resonance peak wavelength can be aligned with the laser wavelength by adjusting device structural parameters (such as grating period, waveguide layer thickness, etc), fabrication errors and measurement environment induce unwanted resonance peak shifts of a fabricated sensor. This issue can be addressed by adjusting the incident angle of the input laser beam on the sensor. Figure 9(a) shows the measured transmission spectrum as a function of the incident angle of a polarized broad-band light source. The angle is measured from a normal incident angle to the sensor surface. As shown in Figure 9(a), the resonance peak splits as the incident angle changes from normal incident angle to the sensor surface. Our fabricated sensor shows multi-mode behavior as shown in Figure 1(b). The first-order and second-order modes appear at around $\lambda=1540\text{nm}$ and $\lambda=1450\text{nm}$, respectively and they exhibit a similar behavior. The measured result indicates that the resonance peak can be adjusted at a rate of 24.5 nm/degree for our device as shown in Figure 9(b). However, it is observed that the reflection efficiency is slightly decreased at different incident angles as shown in Figure 9(a).

V. Conclusions

This paper demonstrates an acousto-optic sensor based on resonance grating waveguide structure that effectively measures ultrasound waves. Static sensitivity of 3.2 pm/kPa is measured from a fabricated sensor. Ultrasound measurements at 20MHz are successfully demonstrated. The fabricated polymer-based AO sensor eliminates complex processing steps (such as dielectric mirror deposition, etc) used by other acousto-optic devices. Depending on the spectral needs, the sensor parameters can be easily modified to suit different spectrum ranges. In addition, for practical purposes, the resonance peak can be tuned at a rate of 24.5nm/degree by adjusting the incident laser angle. Based on the two-dimensional planar structure, the demonstrated sensor can be used to measure applied surface pressure optically, which has potential applications for optical ultrasound imaging and pressure wave detection/mapping. Future work will involve the utilization of lower elastic modulus polymer materials for the waveguide and cladding layer, which can potentially improve the device sensitivity.

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Figure 1.

(a) Schematic of an acousto-optic sensor, (b) Typical resonance spectrum of a fabricated sensor, (c) Ultrasound detection mechanism using the optical peak shift of an acousto-optic sensor

Figure 2.

Fabrication procedure of an acousto-optic sensor. (a) Glass substrate with PDMS layer. (b) NOA-164 is spun and fully cured onto the PDMS layer. (c) S1805 is spun on waveguide layer and exposed using Lloyd's Interferometer custom set up. (d) Overall sensor structure. (e) Digital image of a fabricated acousto-optic sensor. (f) Top view optical microscope image of the fabricated grating. (g) Cross-sectional view image of an example of the diffraction grating.

Figure 3.

(a) Static characterization setup for acousto-optic sensor. (b) Measured reflective peak spectrum as a function of applied pressure.

Figure 4.
Dynamic ultrasound characterization setup.

Figure 5. Spectral characteristics of the fabricated sensor measured with DI water in direct contact with top of grating layer.

Figure 6.

Measured ultrasound waveforms. (a) Echo signal collected from a piezoelectric-based transducer. (b) Acousto-optic signal from the fabricated sensor. (c) Frequency response of a piezoelectric transducer and the fabricated AO sensor.

Figure 7. Acousto-optic response at different incident laser wavelengths demonstrating overall behavior of the fabricated sensor.

Figure 8.
Acousto-optic sensor response of a fabricated sensor at different distances from the excitation ultrasound transducer.

Figure 9. Transmission spectrum of the fabricated sensor as a function of incident angle change. (a) Wavelength versus transmission. (b) Wavelength shift versus incident angle for first-order and second-order modes.