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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.

1. 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 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.

2. Design and fabrication

2.1. Principle of ultrasound detection

The schematic structure of the acousto-optic sensor developed in this paper is shown in Fig. 1(a). This device is based on a

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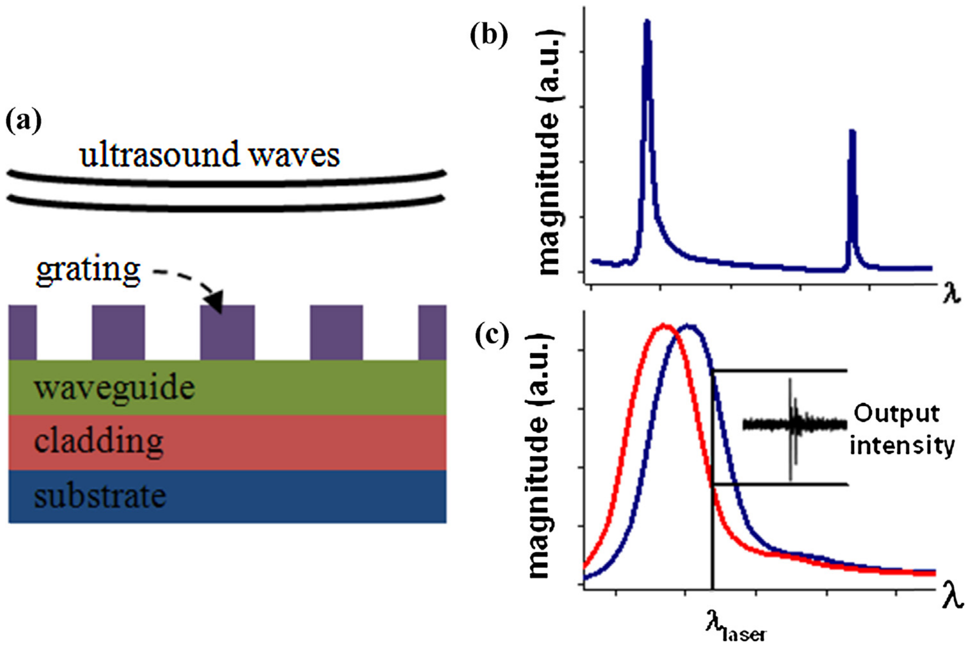

Fig. 1. (a) Schematic of an acousto-optic sensor, (b) Typical resonance spectrum of a fabricated sensor, (c) Ultrasound detection mechanism using the optical peak shift of an acousto-optic sensor.

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. Fig. 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 Fig. 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 photoreciever.

For a given photoreceiver performance ($\Delta V/\Delta I$), 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.

2.2. Fabrication

The fabrication procedure and an image of a fabricated acousto-optic sensor are shown in Fig. 2(a–g). The substrate used is a 1 mm thick, 25.4 mm × 25.4 mm 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 min.

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

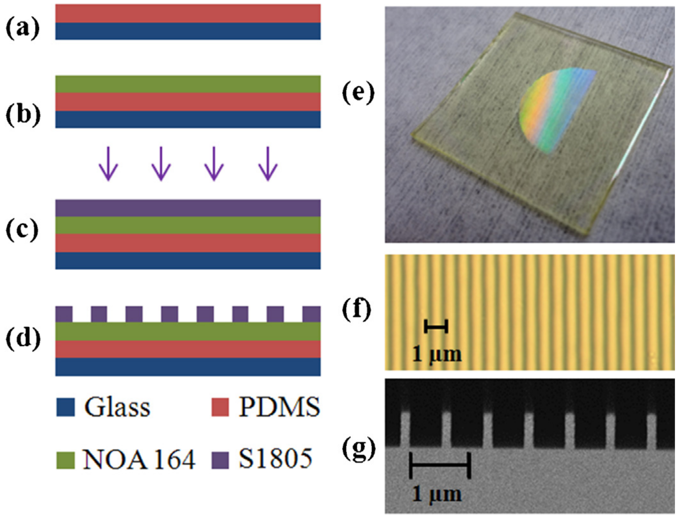

Fig. 2. Fabrication procedure of an acousto-optic sensor. (a) Glass substrate with PDMS layer. (b) NOA-164 is spun and fully cured onto the PDMS layer. (c) S1805 is spun on waveguide layer and exposed using Lloyd's Interferometer custom set up. (d) Overall sensor structure. (e) Digital image of a fabricated 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.