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Elastomeric Polymer Resonant Waveguide Grating based Pressure Sensor

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Abstract

In this paper, we demonstrate an elastomeric polymer resonant waveguide grating structure to be used as a pressure sensor. The applied pressure is measured by optical resonance spectrum peak shift. The sensitivity - as high as 86.74pm/psi or 12.58pm/kPa - has been experimentally obtained from a fabricated sensor. Potentially, the sensitivity of the demonstrated sensor can be tuned to different pressure ranges by the choices of elastic properties and layer thicknesses of the waveguide and cladding layers. The simulation results agree well with experimental results and indicate that the dominant effect on the sensor is the change of grating period when external pressure is applied. 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.

1. Introduction

Monitoring mechanical pressure has been a key sensory element in various applications, from scientific researches to industrial applications [1–4]. Typical pressure sensors can be grouped into optical, piezoelectrical, capacitive, and piezoresistive sensing categories [5–12]. Among these, optical pressure sensors have been of interest because of their high sensitivity, small device size, and potential for high-density arrays. In addition, the optical pressure sensors do not require electrical connections while other approaches require individual electrical connections. These characteristics are well suitable for measuring high-resolution pressure distributions over a two-dimensional structure.

In this paper, we demonstrate a polymer resonant grating waveguide (RGW)-based pressure sensor suitable for two-dimensional optical pressure imaging applications. The critical structure of the sensor is fabricated with elastic polymer materials, which allows designing the pressure sensors for different ranges of pressure measurements. Elastic polymer materials have shown many advantages for flexible electrical pressure sensors [13–15]. These include good pressure sensitivity, simple fabrication, and easy integration, which are also shared in our device structure. Compared to other demonstrated optical resonance-based pressure sensors (e.g. Fabry-Perot etalon-based sensor [10, 11]), the fabrication process of the demonstrated sensor is simpler and does not require high reflective, multilayered dielectric coating. The resonance peak of the sensor can be easily tuned to a different wavelength required in an optical source by changing the grating period. The geometry of

the planar sensor structure is suitable for potential two-dimensional, optical pressure imaging applications such as ultrasound imaging and pressure wave detection/mapping. In the following sections, the design and simulation of the proposed sensor are first discussed. Resonance behaviors of the sensor are discussed for different sensor design parameters. Secondly, the sensor fabrication procedure and measurement are described. The performance and pressure detection mechanism of the fabricated sensor are described when external pressure is applied on the surface of the sensor. Finally, the experimental results are compared and discussed with the simulation results.

2. Design and Simulation

A schematic structure of the sensor is illustrated in Fig. 1. In the demonstrated sensor, the polymer-based RGW structure plays a key role for an efficient pressure sensing element. The structure of the sensor is a planar multilayered structure with a grating layer, a waveguide layer, and a cladding layer on a rigid glass substrate. All layered structures are fabricated from low-cost polymer materials. In our sensor structure, light is illuminated from the glass substrate and the reflected spectral response is measured. When the RGW structure is illuminated with a broad-band light beam, the majority of the light transmits through. Concurrently, strong resonating reflections occur at specific wavelengths and angular orientations of the incident light beam. The pressure sensing mechanism of the demonstrated sensor is based on these optical property changes of the resonance condition during the mechanical strain in the RGW structure. In order to obtain a physical insight of the influence of the light reflection on the different structural parameters, theoretical analysis based on rigorous coupled-mode theory (GratingMOD, Rsoft [16]) are performed with the experimental sensor structures. The sensor has S1805 photoresist as a grating layer, NOA 164 (Norland Products, Inc) as a waveguide layer, and polydimethylsiloxane (PDMS) as a bottom cladding layer on a 1mm thick glass substrate. Here, we choose PDMS polymer as a waveguide cladding material and NOA 164 as a waveguide core material 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 pressure is applied on the sensor structure. Fig. 2(a) shows an example of the reflection spectrum of a RGW structure for normal incident ($\Theta=0$) TE-polarized light (the electric field is parallel to the grating grooves). The parameters at near-infrared wavelengths used for the simulation are $n_1=1.61+i0.001$, $n_2=1.64+i0.0001$, $n_3=1.40+i0.0001$, $n_4=1.45+i0.0001$, $d_1=0.5\mu\text{m}$, $d_2=1.5\mu\text{m}$, $d_3=100\mu\text{m}$, $d_4=1\text{mm}$, grating filling factor of $f=0.5$, and grating period of $\Lambda=1\mu\text{m}$. The exact material parameters are difficult to obtain but they represent reasonable values based on published data from vendors [14, 15, 17]. Imaginary refractive index of each material layer accounts for optical loss in the material. Additionally, the structural thicknesses of the layered materials are chosen considering the fabrication processes in the demonstrated devices.

Based on the simulation, the general device characteristics are obtained and confirmed with experimental results. The resonance location and coupling strength of different modes are affected by the device parameters. The thickness of the NOA 164 waveguide layer affects the number of supported modes. As seen in Fig. 2(a), the simulated structure supports two modes and the spectral full width at half-maximum (FWHM) is larger at the higher order

mode. Therefore, the narrow spectral FWHM of the first order mode is utilized for the sensitive pressure measurement. In addition, optical loss of the waveguide layer (NOA 164) is critical to obtain a good reflection spectrum, which limits the choice of polymer waveguide materials. In the experimental results, NOA 164 is determined to be a suitable waveguide layer. Peak reflection efficiencies at the first order mode changed from 84.7% to 74.3%, and 36.4% for an imaginary part of the refractive index of 10^{-5} , 10^{-4} , 10^{-3} , respectively.

When external pressure is applied to the sensor structure, resonance shifts are obtained through the changes of angular light launching angle, grating period, or waveguide thickness. Fig. 2(b) shows the calculated reflection as a function of the light beam launch angle (Θ). As the launch angle is increased from the normal incident, the resonance peaks are split and diverged into both shorter and longer wavelengths. Fig. 3 shows the calculated resonance peaks of the first order mode as a function of grating period and waveguide layer thickness. While the resonance peak splits when the launch angle changes, the resonance peak wavelength is shifted to a longer wavelength as the grating period or waveguide layer thickness is increased. The measurement results from the fabricated sensors will be discussed in conjunction with the simulated results in the results and discussion section.

3. Fabrication

Fig. 4 shows the fabrication procedure and an image of the fabricated pressure sensor. The sensor uses S1805 photoresist as a grating layer, NOA 164 as a waveguide layer, and PDMS as a bottom cladding layer on a 1mm thick glass substrate. The substrate used was a 1mm thick, $25.4 \times 25.4 \text{ mm}^2$ clear cover glass. Relatively thick glass substrate is chosen to minimize any deformation of the sensor substrate due to the applied pressure during the measuring phase. The glass substrate is cleaned with acetone, methanol and isopropyl alcohol, and subsequently, blow-dried with nitrogen. The substrate is then fully dehydrated at 180°C for 10 minutes. Dow Corning Sylgard 182 PDMS elastomer and curing agent are mixed with a weight ratio of 10:1, respectively. The PDMS mixture is degassed for 30 minutes until air bubbles are removed from the PDMS mixture. Next, the PDMS mixture is poured on top of the glass substrate. In order to get different PDMS layer thicknesses, multiple samples are prepared and spread at different spin speeds. The samples are baked at 100°C for 30 minutes to fully cure the PDMS layer and are allowed to cool down to room temperature. This is followed by an oxygen plasma surface treatment (O_2 , 20sccm, 100W, 20seconds), which enhances the adhesion of the PDMS hydrophobic surface to the subsequent layer. The NOA 164 polymer is spin-coated at 5000 rpm for 30 seconds creating a waveguide core layer thickness of approximately $1.5\mu\text{m}$. The samples are immediately exposed to UV light (at $\lambda = 365\text{nm}$, $120\text{mW}/\text{cm}^2$) for 3 minutes until the NOA 164 is fully cured.

The diffraction gratings are fabricated using a custom built Lloyd's Mirror Interferometer setup with a 30mW diode pumped laser at $\lambda = 405\text{nm}$. To create grating patterns on a sample, S1805 positive photoresist is spin-coated at 5000 rpm on the NOA 164 waveguide surface. The thickness of the photoresist is around 500nm. After baking the sample at 90°C for 2 minutes, it is then exposed in Lloyd's mirror configuration [18]. The sample is positioned on

a sample holder that is equipped with a precise exposure angle controller. This allows the fabrication of the desired grating period. A light shutter is used to control the UV exposure time of the sample and it is set to 19 seconds. The exposed sample is then developed using a solution of Microposit MF-319 developer. Typical developing time is less than 10 seconds. The grating patterns can be seen in samples that are exposed and developed appropriately. The gratings are fabricated with a period of about $1\mu\text{m}$ in order to achieve sensor resonance peaks in the near infrared wavelength range - a range that can be characterized in our measurement setup. Fig. 4(f) shows a picture of a fabricated pressure sensor on a glass substrate. Fig. 4(g) demonstrates a top-view microscope picture of the top view of the S1805 grating patterns.

4. Results and discussion

The characterization setup of the sensor is schematically outlined in Fig. 5. A super-continuum laser is used as an illumination light source onto the sensor. The polarization of the light is controlled with a Glan-Thompson polarizer. A non-polarizing beam splitter is used to guide the reflected light from the sensor to an optical spectrum analyzer that has a wavelength range of 900 to 1700nm. First, the resonant behavior of a fabricated sensor is investigated in ambient air as a function of the incident light wavelength. The incident light polarization is orientated to achieve TE-polarized light (the electric field is parallel to the grating groove direction). Fig. 6(a) shows the measured reflection spectrum of a fabricated device with estimated device parameters of $d_1 = 0.5\mu\text{m}$, $d_2 = 1.5\mu\text{m}$, $d_3 = 300\mu\text{m}$, $d_4 = 1\text{mm}$, and $\Lambda = 1\mu\text{m}$. The measured reflection spectrum shows two resonance modes as our simulation result expects. The first mode is located at $\lambda = 1611.5\text{nm}$ with a FWHM of 3.375nm and the second order mode is located at $\lambda = 1502.32\text{nm}$ with a FWHM of 1.519nm . The measurement agrees with the FWHM trend in the simulation results. In order to test the response of the pressure sensor, a fabricated sensor is sandwiched using two 12.5mm thick acrylic plates with four screws. A Viton o-ring with a 9mm inner diameter and a 1.2mm height is placed on the grating side of the sample to create an airtight chamber. Both top and bottom plastic plates have holes. The top plate hole is sealed with Tygon tubing to supply pressurized nitrogen (P2) air into the air chamber (atmosphere pressure, P1) using a pressure regulator. The differential applied pressure ($P = P_2 - P_1$) ranges from 0 psi to 50 psi, which converted to 0~345kPa. The hole in the bottom plate allows collimated laser light to illuminate the sensor through the glass substrate. Fig. 6(b) shows the spectral response of the first order mode as a function of applied pressure. The measured spectral response in the fabricated sensor clearly distinguishes the applied pressure ranged from 0kPa to 345kPa. To identify the origin of the spectral response characterization, sensors with different PDMS thicknesses are fabricated and tested. The measurement results are summarized in Fig. 7. The general observation from the measured results shows that the resonance peak shifts to a longer wavelength as the applied pressure increases, while no resonance peak splitting occurred. This indicates that the launching angle of the illuminated beam into the sensor is not affected for the current pressure measurement condition considering the simulation result shown in Fig. 2(b).

Theoretically, the change of PDMS layer thickness does not create the resonance wavelength shift when there is no pressure applied. This is because the resonance grating

waveguide structure is mainly affected by the grating layer and waveguide layer structures. Thereby, the measured shift in peak resonance wavelength indicates either a change in waveguide layer thickness or grating period. As the simulation results in Fig. 3 demonstrates, a resonance peak shift to a longer wavelength correlates to an increase of grating period and waveguide layer thickness. Since air pressure is applied directly on top of the grating side of the sensor, the force of the pressure is expected to press against the top of the sensor. This pressure leads to a compression of the waveguide layer and, thus, a decrease in its thickness. Consequently, this causes a deformation of the S1805 layer so that the grating period is effectively increased. The measured peak wavelength shift shown in Fig. 7 indicates that the wavelength shift increases with an increase of PDMS layer thickness. Clearly, by varying the thickness of the PDMS layer, the sensor sensitivity can be tuned to different pressure ranges. The experimental results show sensitivity as high as 86.74 pm/psi or 12.58 pm/kPa for sensors with a 550 μm thick PDMS layer. The demonstrated sensor also exhibits good repeatability when the applied pressure is increased and decreased successively. Considering that the demonstrated sensor is fabricated using elastic polymer materials, the sensor is not suitable for high temperature and high pressure applications. It will be more suitable for applications where their environmental changes (temperature and humidity) are minimal.

5. Conclusions

In this paper, a polymer resonant grating waveguide based pressure sensor is demonstrated. The elastic properties of the NOA 164 waveguide layer and the PDMS cladding layer allow the sensor to effectively measure applied pressure ranges (P) from 0 kPa to 345 kPa. Potentially, the sensor pressure sensitivity can be improved by utilizing materials with distinct elastic properties and by also varying the thicknesses of the layered structures. The simulation results concur with the experimental results and indicate that the dominant effect exhibited by the sensor is the change of its grating period when external pressure is applied. Based on the two-dimensional planar structure, the demonstrated sensor can be used to measure applied surface pressure optically. Future work will include the temporal response characterizations of the demonstrated pressure sensor and the demonstration of two-dimensional, nonuniform, surface pressure measurements, which will be useful for ultrasound imaging and pressure wave detection and mapping applications.

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Figure 1.

A schematic design structure of the resonance grating waveguide based sensor.

Figure 2.

(a) Calculated reflection efficiency of TE-polarized light excitation at normal incident and
 (b) at a function of incident launch angle.

Figure 3.
Calculated reflection efficiency of the first order mode as a function of grating period (a) and waveguide thickness (b).

Figure 4. Fabrication procedure (a–e) of the sensor and an example of a fabricated sensor (f). (g) S1805 grating fabricated using laser interference lithography.

Figure 5.
Characterization setup of the resonance grating waveguide based pressure sensor.

Figure 6.

An example of the measurement results of a resonance grating waveguide based pressure sensor. (a) Spectral resonance response at no applied pressure. (b) Spectral resonance response at a function of applied pressures.

Figure 7. Measurement resonance wavelength shifts of the first order modes of pressure sensors at different thickness of PDMS cladding layers.