Highly Sensitive Refractive Index Sensor Based on Polymer Long-Period Waveguide Grating With Liquid Cladding

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Abstract: We propose a novel structure and unique sensing mechanism bio-chemical sensor which is fabricated by a polymer long-period waveguide grating with the detection liquid directly as the waveguide cladding. Quantitative detection is realized from analyzing the output absorption spectrum and resonant wavelength shift related to the liquid detection concentration. The proposed polymer long-period waveguide grating based liquid refractive-index sensor is developed experimentally, the high sensitivity of 1.01×10^4 nm/RIU is achieved, and the temperature stability coefficient is 1.47 nm/℃. Theoretically and experimentally, this work has been demonstrated to have potential application in chemical and biological detections and may provide an important technical support for solving today's increasingly serious civil problems such as food safety and drug safety, which will also have the important scientific significance and application prospects.

Keywords: Optical sensor; polymer waveguides; long-period waveguide gratings; liquid cladding

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1. Introduction

Optical refractive index (RI) sensor exhibits many interesting properties including high sensitivity, fast response, wide dynamic range, multiplexing capability, remote sensing capability, freedom from electromagnetic interference, and capability to operate in harsh environments. A semiconductor nanowire RI sensor is demonstrated [1], and the sensitivity is as high as 235 nm/RIU (refractive index unit, besides, by choosing proper diameter, and the scattering efficiency peak can be tuned into the optimum spectral region (600 nm – 900 nm) for biosensing. Optical fiber sensors based on the long-period fiber grating (LPG) are proposed for an RI sensor [2–4]. The cladding diameters of the LPG between the core and detection liquid have effects on the transmission spectrum of each cladding mode to varying degrees, so that we can achieve the highly sensitive long-period fiber gratings refractive index sensor by reducing the cladding diameter for the appropriate cladding mode. The sensitivity normally is as high as the order of 10^3 nm/RIU) with the suitable overlay thickness, and the measurable dynamic range of the sensitive film refractive index is available to 0.01.

However, considering the development of sensor-on-chip (SOC), and the compatibility and integration of the waveguide sensor and

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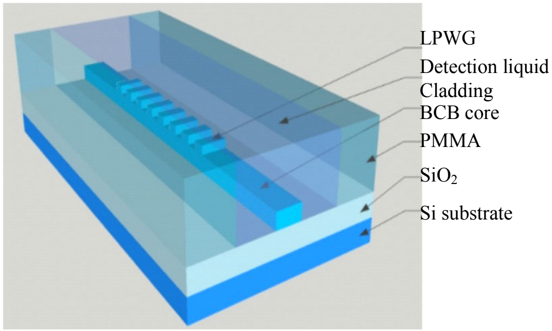
correspondence signal process system, the planar waveguide has more priority in the application of sensor fields. Currently, different working principles such as micro-ring/micro-cavity [5–8], Mach-Zehnder (M-Z) interferometer [9, 10], and slot waveguide [11] are widely used to form sensors, and the corresponding sensor sensitivity is normally in the order of 10^2–10^3 nm/RIU.

A long-period waveguide grating (LPWG) formed in a single mode waveguide can couple light from the guided core mode to a selected cladding mode at a specific resonant wavelength, thus allowing a distinct attenuation band in the transmission spectrum [12]. Over the last few years, a range of LPWG devices, which include variable attenuators [13–15], tunable optical filters [16, 17], and add-drop multiplexers [18, 19], have emerged. The use of an LPWG for RI sensing has been studied, and the sensitivities of 10^2 nm/RIU – 10^4 nm/RIU are demonstrated [20, 21], for example, a sensitivity of 5.7×10^4 nm/RIU has been achieved with an optimized prism-based long range surface plasma (LRSP) sensor [22], which is higher than the sensitivity of a short range surface plasma (SRSP) sensor (6×10^3 nm/RIU) by an order of magnitude [23].

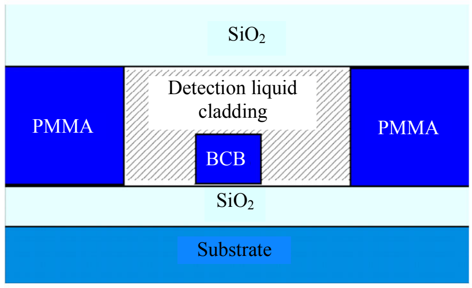
In this paper, we propose and experimentally demonstrate a polymer LPWG assisted refractive index sensor formed with the detection liquid directly working as a waveguide cladding. The typical fabricated device shows a sensitivity of 1.01×10^4 nm/RIU at the spectral range of 1520 nm – 1610 nm. The temperature stability coefficient is measured to be 1.47 nm/℃, which has negligible contribution to the sensitivity obtained. This technique opens a new way of the liquid phase spectroscopy that can be of use for many biotechnology and environmental applications.

2. Design method and fabrication

The LPWG formed structure in this work is schematically shown in Fig. 1(a), and the waveguide materials and cross section view of the proposed sensor can be clearly seen from Fig. 1(b). When a broadband light source (1520 nm – 1610 nm) is introduced into the waveguide core, there will be a significant spectral dip at the resonant wavelength on the output spectrum according to the coupled mode theory of the LPWG. By measuring the resonant wavelength shifts with the corresponding refractive index changes, we can calculate the refractive index of the detection liquid.



(a)

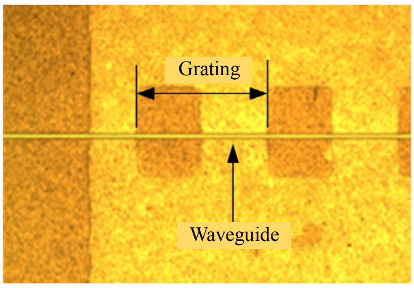


(b)

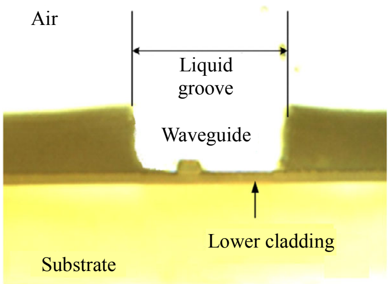
Fig. 1 Schematic diagram of (a) three-dimensional structure and (b) cross-section of the LPWG based sensor.

The geometry of the straight waveguide is designed by the methods of the effective refractive index method and COMSOL simulation. The dimensions of the designed waveguide and LPWG are as follows: the core width and height are both 3 μm, the liquid cladding width is 15 μm, and the height is 10 μm. The period of the LPWG is calculated to be 103 μm according to the phase matching equation. Considering the transmission loss, total chip length, and the coupling efficiency, we choose a grating depth of 250 nm in this work. Finally, the grating coupling coefficient 153.2 m^{-1}

and coupling length 10.3 mm are calculated according to the coupled mode theory.



(a)



(b)

Fig. 2 Microscope images of fabricated chip: (a) without groove etching but with grating etching and (b) cross-section view after groove etching.

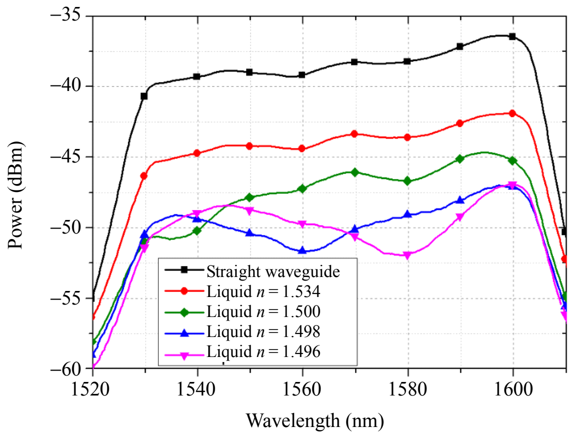
The sensor chip is fabricated by ultraviolet (UV) exposure, inductively coupled plasma, magnetron sputtering, and other standard procedures. The microscope images of the LPWG and waveguide are shown in Figs. 2(a) and 2(b). The fabricated waveguide core width and height are 3.2 μm and 2.9 μm, respectively, the LPWG period is 103.8 μm, and the coupling length is about 10.5 mm. The poly methyl 2-methylpropenoate (PMMA) cladding thicknesses is 10.7 μm. The liquid groove width is 14.6 μm and is slightly asymmetric around the waveguide core. The sidewalls are rough due to the reactive ion etching device limitation. Overall, the fabricated device dimensions are within acceptable tolerances for achieving the reported performance.

3. Experimental results

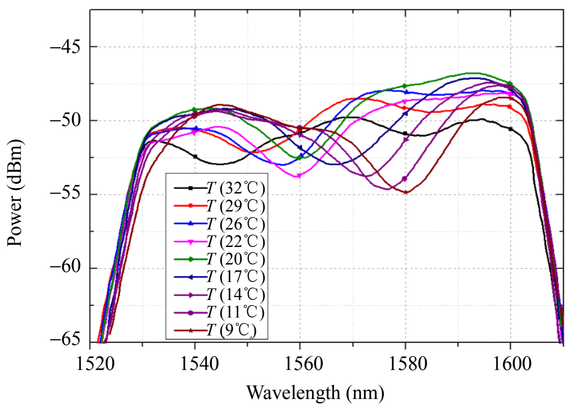
We adjust the exposure so that the photoresist operates in a linear response regime. With exposure by the extreme ultraviolet lithography (EUV) laser, the holographic interference pattern generated by the reference and the object beams is recorded in the photoresist and converted to a surface modulation after the development. Thus, the holograms are recorded as a relief pattern in the surface of a photoresist deposited on a Si wafer.

For our LPWG based sensor, the RI sensitivity refers to the transmission spectrum change due to the RI change of the liquid cladding. It is measured by dropping the certified index liquids (supplied by Cargille Laboratories, Inc.) into the cladding groove. During the measurement, the substrate of the LPWG is kept at the temperature of 24 ℃ to minimize thermal perturbation. The transmission spectrum is measured with an optical spectrum analyzer. As can be seen in Fig. 3(a), the lowest three transmission spectra with different resonant peaks correspond to different detection liquids, comparing with the top output line from the straight waveguide without the LPWG. It can be clearly seen that the central resonant wavelength of the output spectrum shifts to the shorter wavelength when the liquid RI is gradually increased, which is consistent with the theoretical prediction. The full width half maximum of the proposed device is wide, but it will not influence the application of the sensor, because we care about the resonant wavelength or just the peak wavelength shift. Besides, from the red line (liquid RI of 1.534) next to the top one, we find that the resonant peak has shifted out of the wavelength range, which indicates a quite sensitive sensor. Finally, we calculate the sensitivity to be 1.01×10^4 nm/RIU.

To characterize the temperature effect on the sensor stability, measurements are taken at various working temperatures. It can be seen from Fig. 3(b) that the resonant wavelength peak of the sensor shifts to the shorter wavelength while the temperature gradually increases from 9 ℃ to 32 ℃. The central resonant wavelength is plotted as a function of temperature shown in Fig. 4, and the temperature stability coefficient (also be noted as temperature sensitivity in some literatures [24]) is calculated to be 1.47 nm/℃, which is small compared with the sensitivity of the sensor, and it is also a high temperature sensitivity compared with the results existed [25].



(a)



(b)

Fig. 3 Transmission spectra of the fabricated waveguide sensors: (a) measured by using different refractive indexes of liquid and (b) measured in different operation temperatures.

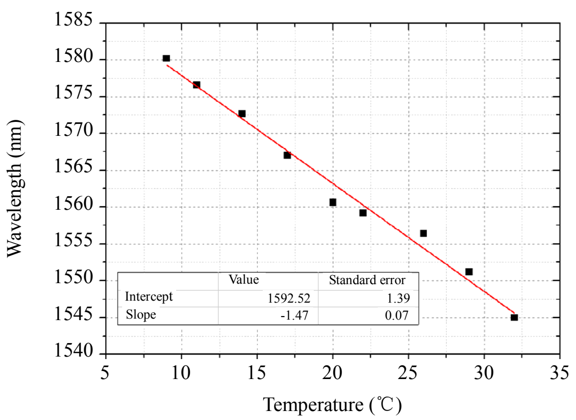


Fig. 4 Shifted resonant wavelength plotted with operation temperatures.

4. Discussion

As far as we know, this work has been proposed for the first time as a refractive index sensor based on the polymer long-period waveguide grating which uses the detection liquid directly as its cladding layer, so that this sensor can work as a label-free sensor which can avoid the interference of the calibrator to the sample and enable real-time on-line monitoring. From the experimental results, we can see that the sensitivity of the proposed sensor has been improved an order of magnitude to 10^4 nm/RIU, thus the refractive index measurement range is limited by the waveguide material which can be used currently. However, we believe that this limitation can be reduced or eliminated with the development of material science.

Experimentally, we have demonstrated a maximum temperature sensitivity of 1.47 nm/℃ which is 200 times higher than that of a tranditional temperature sensor. The normal operation temperature change has a negligible influence on the sensor sensitivity. When the temperature increases, the refractive index of polymer will be decreased because of the negative thermo-optic coefficient, so the effective refractive index of the waveguide core will be decreased but the effective refractive index change of the liquide cladding can be neglatible, so the resont wavelength will be decreased (shift to the shorter wavelength) according to the coupled mode equation, which is the reason why the temperature increase induces a shorter wavelength shift.

5. Conclusions

In summary, we have experimentally investigated the RI sensitivity of the LPWG based polymer waveguide sensor. The results indicate that the transmission spectrum of the LPWG is highly sensitive to the RI of the waveguide cladding detection liquid. When the refractive index ranges out of 1.494 – 1.500, a larger wavelength range of the laser source needs to be used for observing the effective spectrum. Obviously, with different grating periods in correspondence of waveguide dimensions toward a multi-target detection, our study indicates that the LPWG based RI sensor may have potential applications in the on-chip liquid phase spectroscopy. Considering these aspects, our work predicts that the LPWG based sensors have promising applications in diverse sensing devices, especially in biosensing.

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