Chemical sensor using Bragg grating based optical ridge waveguide with polydimethysiloxane as top layer

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ABSTRACT

The polymer polydimethylsiloxane (PDMS), which is used as a cladding layer in waveguide-based optical components, is sensitive to some organic compounds. Absorption of organic compounds by PDMS results in changes to the polymer's refractive index and absorption spectrum. In this work, a compact and highly sensitive organic compound sensor based on an evanescent coupling of a Bragg grating ridge waveguide into a PDMS top cladding layer is proposed. The sensor is an open-top Ge-doped SiO_2 ridge waveguide possessing a photoinduced Bragg grating in the waveguide core that has a cladding overlayer of PDMS. When an analyte is applied to the top of the waveguide, changes to the refractive index and absorption of the PDMS layer result in shifts to the Bragg resonance of the core grating. The birefringence, and temperature sensitivity of the sensor are examined.

Keywords: PDMS, Bragg gratings, chemical sensors, ridge waveguides

1. INTRODUCTION

Using a surface relief D-shaped fiber Bragg grating and a polydimethylsiloxane (PDMS) layer, a volatile organic compound sensor has been developed [1-2]. To increase effectively the interaction between the evanescent tail of the modal field and the surrounding media, complicated fabrication processes were required to change the geometry of the fiber. The processes included: 1) hydrofluoric acid etching to reduce the cladding thickness of the flat D-surface of the fiber above the core; . 2) spinning photo resist onto the flat fiber surface and patterning a grating into the resist by using a two-beam interference method; 3) transferring the grating pattern into the glass by reactive ion etching with aCF_4 plasma. 4) depositing a buffer over the grating to provide and maintain the index contrast. 5) spinning PDMS on the evaporated sapphire. With a relatively simple fabricating processes, a high sensitivity and thermally stable chemical sensor is fabricated using the evanescent field of a ridge waveguide. The sensor consists of an open-top Ge-doped SiO_2 ridge waveguide with UV-induced Bragg grating in the waveguide core. A top layer of PDMS is spun on the top of the waveguide as the sensitive coating for volatile organic compounds. Unlike the surface relief D-shaped fiber Bragg grating, UV-induced Bragg grating exists in the core of the waveguide which is adjacent the sensing PDMS layer. No other interstitial deposited layer is needed. The interaction between the evanescent tail of the modal field in the ridge waveguide core and the surrounding media is stronger than that in the D-shape fiber sensor. The sensitivity of the ridge waveguide Bragg grating sensor with PDMS is very high. As shown in Fig. 1, the grating structure is incorporated into a ridge waveguide architecture. When a probing light source is coupled into the core of the

Fiber Optic Sensors and Applications VI, edited by Eric Udd, Henry H. Du, Anbo Wang, Proc. of SPIE Vol. 7316, 73160G

ridge waveguide, the evanescent field of the fundamental guided mode of the ridge waveguide propagates along the top surface accessing the surrounding medium. The thickness of the evanescent field is less than λ, the wavelength of the light coupled into the core of the waveguide. When the top of the ridge waveguide is covered with PDMS as the top layer, a portion of the fundamental mode of the waveguide couples evanescently into the film changing the effective refractive index n_{eff} of the guided core mode. When an analyte is applied to the top of PDMS, changes to the refractive index and absorption of the PDMS layer result in shifts to the Bragg resonance of the core grating such that

$$\Delta\lambda_B = 2\Lambda\Delta \boldsymbol{n_{eff}} \quad (1)$$

where λ_B is the resonance of Bragg grating, Λ is the grating period, and n_{eff} depends on the core index n_c and the PDMS cladding index n_P. Any change to n_P results in shifts of λ_B. In this work, Bragg gratings are inscribed into different core size ridge waveguides with PDMS spun on the top of the waveguide. PDMS is a desirable polymeric material for photonic components. It has a relatively low refractive index 1.43

compared to silica 1.4545 at the 1.55 μm telecommunication wavelength, good spectral transmission in the near-infrared range, and has high chemical and mechanical stability, making it well suited as a waveguide cladding material. PDMS is also chemically selective, being more penetrable to large, hydrocarbon-based volatile organic compounds than to polar molecules such as water and low molecular weight gases, such as oxygen and helium. The changes in the polymer's refractive index and absorption spectra are dependent on the type of chemical and amount absorbed. The absorption of volatile organic compounds into the polymer is naturally reversible, as the small amount of absorbed volatile organic compounds are re-released into the environment once equilibrium no longer exists. PDMS exhibits these selective transport properties in both liquid and gaseous environments. The changes in the polymer's physical properties such as refractive index and absorption spectrum is attributed to the absorption of volatile organic compounds into the polymer. The PDMS changes refractive index to more closely match the refractive index of the absorbed analyte [3]. Acetone is chosen for this experiment as it has high solubility in PDMS. The sensitivity of the sensor is investigated by measuring the relationship between $\Delta\lambda_b$ and acetone concentration for the devices with waveguide core size of 7.7 μm × 5.6 μm. The results show that the

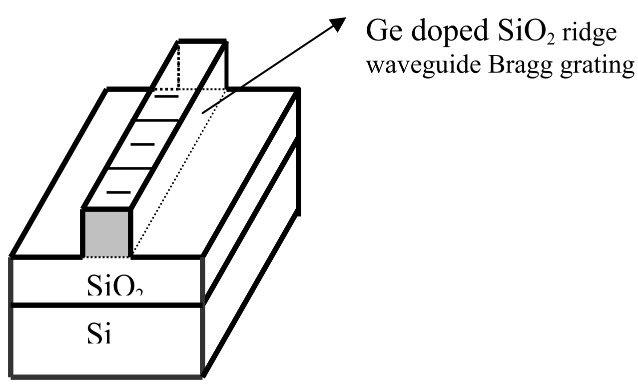

Fig.1 WBG ridge waveguide

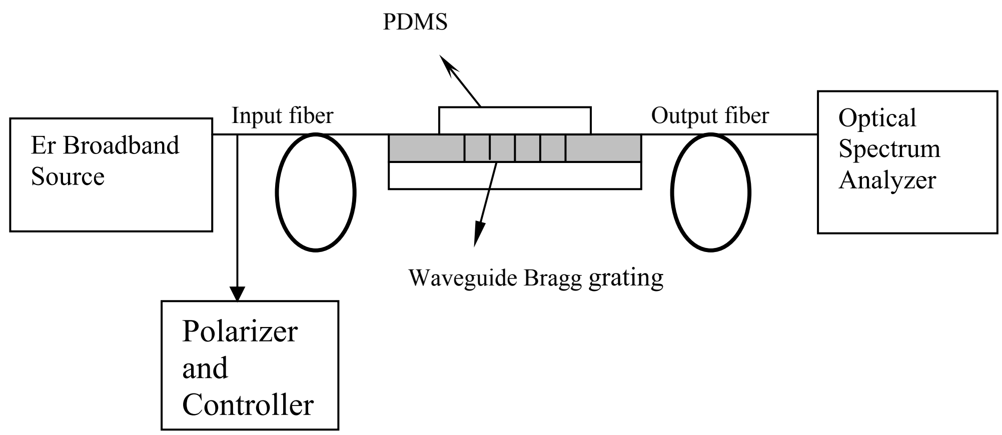

Fig.2 The configuration of measurement setup.

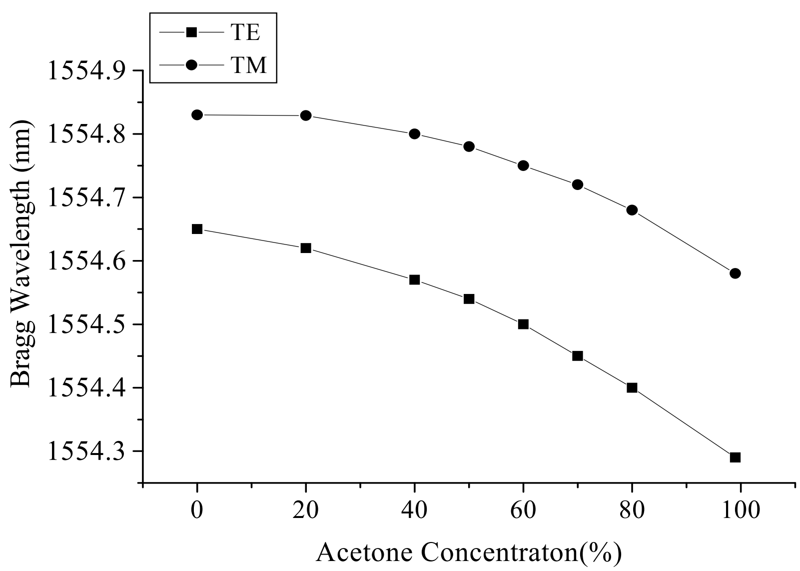

Fig.3 Bragg wavelength shifting with acetone concentration changes

waveguide device has a high sensitivity. Both TE and TM Bragg resonances of the device are sensitive to the change of the analyte concentration. The thermal sensitivity of the chemical sensor is tested by measuring the shifts of Bragg wavelength with the change of the temperature. Although the thermo-optic coefficient of PDMS is high order compared with Silica, the chemical sensor has a low temperature sensitivity due to the counter-balancing of the thermal dependence of the refractive index of PDMS and the thermo-optic and thermo-mechanical effects of the silica waveguide.

2. EXPERIMENT AND RESULT

The structure of the sensor is shown in Fig.1. The ridge waveguides were fabricated on a 6 ± 0.5 µm thick Ge-doped SiO_2 layer that was grown by flame hydrolysis deposition (FHD) on a 7 µm layer of thermal silicon dioxide on silicon. The core layer index, n_g was measured before etching by prism coupling at 1537 nm to be 1.4545 ± 0.0004. The bottom cladding index n_s was 1.4436, which was 0.75 ± 0.07 % less than n_g. The ridges were produced using standard photolithography and reactive ion etching (RIE) using a CHF_3/O_2 gas mixture. The dimensions of the waveguides, as measured using scanning electron microscopy were 7.7 µm × 5.6 µm. The distance between two adjacent ridges was 75µm. On a wafer patterned with different core size ridge waveguides, Bragg gratings were written using a single zero-order nulled phase mask and an ArF excimer laser with an emission wavelength of 193 nm. With an UV cylindrical lens, the laser beam was focused to a spot size of 5 mm × 300 µm onto the wafer surface. A strong Bragg grating with index modulation $\Delta n \sim 9 \times 10^{-4}$ was induced in the hydrogen loaded 7.7µm × 5.6 µm waveguide with 40Hz, 100 mJ/cm^2/pulse of polarized UV irradiation (oriented normal to the waveguide axis). The total UV exposure for the fabrication of the Bragg grating with –21 dB transmission and 0.7 nm bandwidth is 1 kJ/cm^2. The section of the waveguide that contains the 5 mm long Bragg grating was then coated with 1 mm thick layer of PDMS. The diagnostic setup is shown in Fig. 2. To monitor the polarization dependence of the spectral response of the grating, broadband light from a 980 nm-pumped erbium doped fiber was passed through a polarization controller and coupled into the ridge waveguide Bragg grating. The wavelengths for TE and TM polarizations were distinguished using a half wave plate. The transmitted light was out-coupled into a single-mode fiber and monitored by using an optical spectrum analyzer. The Bragg wavelength shifted with changes in the acetone concentration. The results are shown in Fig. 3. Both TE and TM Bragg resonances were sensitive to the refractive index change of the polymer film. The thermal experiments was done by fixing the pressure and varying the temperature stepwise from room temperature to ~ 80 ^oC with a thermoelectric peltier device. The results show that the Bragg wavlength of the ridge waveguide with PDMS shifted much more with increasing temperature, as much as 0.05 nm/ ^oC.

3. DISCUSSION

The ridge waveguide structure is as shown in Fig.1. Some analytic methods such as the effective-index method, Marcatili's method, the mode-matching method and the finite-element method were used to analyze the ridge waveguide. However, many of these analytical methods require complicated math computations and detailed knowledge of the physical properties of the waveguides, which are not always easy to measure. A simple numerical method [4] was developed to analyze the dispersion characteristics of the guided modes of a strip waveguide. The effective indices n_{TE} and n_{TM} of the TE and TM mode of the ridge waveguide were given by

$$n_{TE}^2 = ń_{TE}^2 - m^2\pi^2/4a^2k^2 \, [1- 2/ak(n_g^2-n_p^2)^{1/2}] \tag{2}$$

and

$$n_{TM}^2 = ń_{TM}^2 - m^2\pi^2/4a^2k^2 \, [1- 2/ak(n_g^2-n_p^2)^{1/2}+ 2(n_g^2-n_p^2)^{1/2}/ ak\, n_g^2] \tag{3}$$

where $k = 2\pi/\lambda$ is the free-space wave number. $ń_{TE}$ and $ń_{TM}$ are the effective indices of TE and TM modes of three layer slabs, respectively, a is the width of the ridge waveguide. n_g, n_s, n_p are the refractive indices of the core, the substrate and the top layer, respectively. Here, with Eqs.(2) and (3), the sensitivities of TE and TM mode of the ridge waveguide are derived as

$$S_{TE} = \partial n_{TE} / \partial n_p = Ś_{TE} \,(ń_{TE} / n_{TE}) + (n_p / n_{TE})(m^2\pi^2/4a^3k^3)[1/(n_g^2-n_p^2)^{3/2}] \tag{4}$$

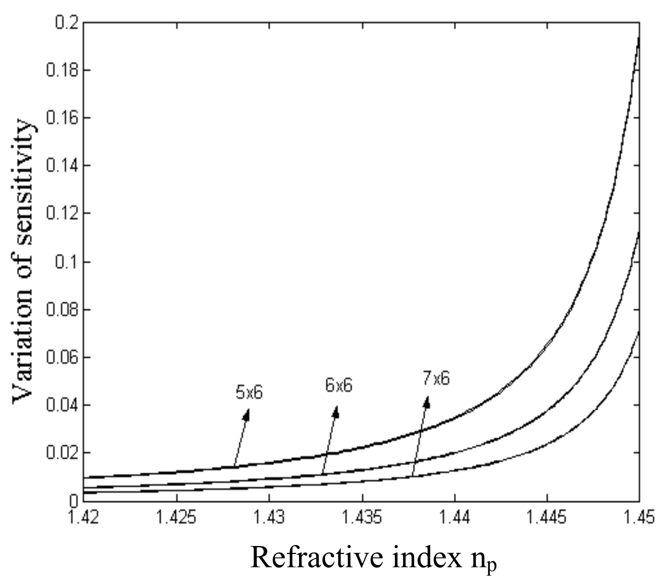

Fig. 4 The variation of sensitivity with core size a and low refractive index $n_p$of polymer film.

and

$$S_{TM} = \partial n_{TM} / \partial n_p = Ś_{TM} \,(ń_{TM} / n_{TM}) + (n_p / n_{TM})(m^2\pi^2/4a^3k^3)[1/(n_g^2-n_p^2)^{3/2} +1/ n_g^2(n_g^2-n_p^2)^{1/2}] \tag{5}$$

where $Ś_{TE} = \partial ń_{TE} / \partial n_p$ and $Ś_{TM} = \partial ń_{TM} / \partial n_p$. $Ś_{TE}$ and $Ś_{TM}$ are the sensitivities of TE and TM modes of three layer slabs,

respectively. $S_{TE,}$ S_{TM} are the sensitivities of TE and TM modes of ridge waveguides, respectively. As $ń_{TE} \approx n_{TE}$ and $ń_{TM} \approx n_{TM}$, the first terms in Eqs. (4) and (5) are dominated by $Ś_{TE}$ or $Ś_{TM}$. By the normalized analysis of a slab waveguide evanescent-wave sensor, the expressions of $Ś_{TE}$ and $Ś_{TM}$ are given in Ref. [5]. The optimization results for all slab waveguide sensors were achieved. However, the results can not be applied directly for the ridge waveguides due to the structural difference of the three layer slab waveguides and the ridge waveguides. The structural characteristic of ridge waveguides is reflected in the second term of Eqs. (6) and (7) by the parameters a, n_g, n_t. We are interested in the contributions of the second terms to S_{TE} or S_{TM}. The results are plotted in Fig5. It is clear that the sensitivity increases slowly in the low refractive index, but increases rapidly as the index of the surrounding medium approaches that of the waveguide. The sensitivity increases as the core width decreases. The thermal sensitivity of the chemical sensor is tested by measuring the shifts of Bragg wavelength with the change of the temperature. The refractive index vs. thermo-optic coefficient index dn_p/dT for PDMS and SiO_2 are about -4×10^{-4} and 1.2×10^{-5}, respectively. By the experimental sensitivity curve of the ridge waveguide [6], we have $d\lambda/dn_p = 30$nm at the index 1.400. Therefore, the actual change of Bragg wavelength resulted by the thermo-optic coefficient of PDMS is estimated as – 12 pm/ ^oC, which can be balanced by the thermo-optic effect of the silica ridge waveguide of +11 pm/ ^oC. However, due to the stresses developed from the mismatch in the thermal-mechanical coefficients between the polymer and the ridge waveguide material silica, the sensor is sensitive to temperature variations. The device is sensitive to the temperature. The temperature sensitivity of the pressure sensor can be compensated by using the sensitive difference of TE and TM modes for pressure. The phenomenon will be further explored in our next work.

4. CONCLUSION

Based on the optical evanescent field of a ridge waveguide, and the properties of PDMS which has a relatively low refractive index and is chemically selective, an organic compound sensor has been developed. Compared with the sensor made with D fibers, the sensor consisting of a ridge waveguide Bragg gratings with a PDMS top layer has higher sensitivity and better thermal stability. The fabricating processes of the ridge waveguide sensor are simple.

REFERENCES

1. John D. Gordon, Tyson L. Lowder, Richard H. Selfridge, and Stephen M. Schultz, "Optical D-fiber-based volatile organic compound sensor," Appl. Opt. 46(32), 7805-7810 (2007).
2. Tyson L. Lowder, John D. Gordon, Stephen M. Schultz, and Richard H. Selfridge, "Volatile organic compound sensing using a surface relief D-shaped fiber Bragg grating and a polydimethylsiloxane layer," Opt. Lett. 32(17), 2523 – 2525 (2007).
3. Karin Spaeth, Gerolf Kraus, Gunter Gauglits, "In-situ characterization of thin polymer films for applications in chemical sensing of volatile organic compounds by spectroscopic ellipsomtry, " Fresenius J. Anal. Chem. 357, 292-296 (1997).
4. Kin S. Chiang, "Dispersion Characteristics of strip dielectric Waveguides", IEEE Trans. Microwave Theory and Tech. 39(2), 349-352 (1991).
5. Olivier Parriaux, and G. J. Veldhuis, "Normalized Analysis for the Sensitivity Optimization ofIntegrated Optical Evanescent-wave sensors", Journal of Lightwave Technology 16 (4), 573 -582 (1998).
6. . X. Dai, S. J. Mihailov, C. L. Callender, C. Blanchetière, R. B. Walker, "Ridge-waveguide-based polarization insensitive Bragg grating refractometer", Meas. Sci. Technol. 17, 1752-1756(2006).