

Side-Polished Fiber Optic Pressure Sensor based on Stress Optical Property of Polymer Planar Waveguides

Jong-Kuk Yoon, Sang-Woo Kim, Gyoo-Won Seo, Yun-Sik Yu¹,
Dae-Hyuk Kwon² and Shin-Won Kang^{3*}

Department of Sensor Engineering, Kyungpook National University, Taegu 702-701, South Korea

¹Division of Science and Technology, Donggeui University, Pusan 614-714, South Korea

²Department of Electronic and Information Engineering, Kyungil University,
Kyungsan 712-900, South Korea

³School of Electronic and Electrical Engineering, Kyungpook National University,
Taegu 702-701, South Korea

(Received August 10, 2001; accepted March 18, 2002)

Key words: side-polished optical fiber, evanescent wave, polarization dependence, stress optical coefficient, planar waveguide.

A pressure sensor with a high measurement capability and wide range, based on a single mode side-polished fiber and polymer planar waveguide, is presented. It was found that resonance wavelength shifts occur due to variations in the refractive index of polymers relative to pressure, and this sensitivity depends on the waveguiding polymer. A symmetric structure for the planar waveguide was adopted to eliminate polarization dependence which is inevitable with a side-polished fiber. THB-30, AZ1512 and polystyrene were used as the planar waveguide polymers, and resonance wavelength shifts caused by applied pressure were exhibited at 0.16 nm/bar, 0.033 nm/bar and 0.024 nm/bar, respectively.

1. Introduction

Recently, evanescent field coupling between a side-polished single-mode optical fiber and a polymer planar waveguide overlay has been an area extensively researched because of its mechanical stability, low insertion loss, and potential for remote measurement and various applications such as optical filters,⁽¹⁾ optical polarizers,⁽²⁾ optical switches,⁽³⁾ and modulators.⁽⁴⁾ An evanescent-type coupler can also be applied to pressure sensors through

*Corresponding author, e-mail address: swkang@knu.ac.kr

changing the refractive index of the planar waveguide (PWG).

There have been many previous reports on pressure sensors based on Fiber Bragg Grating, piezoresistivity, and semiconductors.^(5,6) However, despite the recent progress, such pressure sensors are unsuitable for high-pressure measurements and lack a wide-range capability and good reliability. Accordingly, new pressure sensors are required to facilitate high-pressure sensing and wide-range measurability, while also providing better reliability and easier measurement for a variety of applications.

In this paper, a novel pressure sensor is proposed which is based on the resonance wavelength shift of a single mode fiber-to-PWG coupler. Polymers that change their refractive index according to variations in the applied pressure are used for the PWG. The sensitivity is controlled by using various polymers with different stress optical coefficients. In addition, the stress optical coefficients of the polymers can be calculated indirectly.

2. Theoretical Principle

A longitudinal view of the proposed sensor is shown in Fig. 1. The proposed sensor has the structure of a fiber-to-PWG coupler and is composed of a side-polished single mode fiber and a multimode PWG, as shown in Fig. 1.

The refractive indices of the fiber core, fiber clad, guiding layer of the PWG, and clad of the PWG are n_f , n_1 , n_0 , and n_2 , respectively. The bending radius of the fiber, residual clad thickness of the fiber, and thickness of the PWG are denoted as R , g_0 , and d_0 , respectively. P_1 and P_0 refer to the optical powers at the input and output ports, respectively. When the fiber mode is phase matched with a compound waveguide mode, optical resonant power is evanescently coupled from the fiber core into the multimode PWG at a particular wavelength. The peak dip wavelengths (resonant wavelengths) for both orthogonal polarizations can then be easily calculated using the eigenvalue equation of the PWG and fiber modes. The eigenvalue equation of the m -th order PWG mode can be expressed as follows,

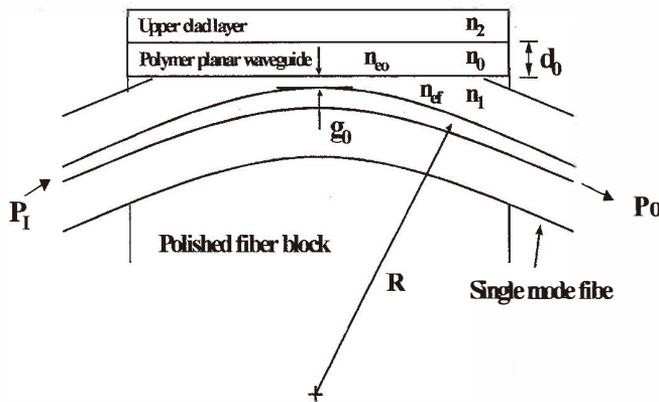


Fig. 1. Schematic configuration of fiber-to-planar waveguide coupler applied to pressure sensor.

when the dispersion and birefringence of the material are not considered⁽⁷⁾:

$$\frac{2\pi d_0}{\lambda} (n_0^2 - n_{\text{eo}}^2)^{\frac{1}{2}} = m\pi + \varphi_1 + \varphi_2 \quad (1)$$

where λ is the input free space wavelength. φ_1 and φ_2 , given by the following equation, are the phase shifts of the guided mode at the lower and upper planar waveguide boundaries, respectively.

$$\varphi_i = \tan^{-1} \zeta \frac{(n_{\text{eo}}^2 - n_i^2)^{\frac{1}{2}}}{(n_0^2 - n_{\text{eo}}^2)^{\frac{1}{2}}} \quad (i = 1 \text{ or } 2) \quad (2)$$

ζ is the polarization-dependent constant (1 for TE, n_0^2 / n_i^2 for TM). The structural birefringence of the PWG, i.e., the effective refractive index difference between the TE and TM mode, results from the fact that the TE and TM polarizations have different boundary conditions. TE has a continuous tangential electric field at its boundary, whereas TM has a discontinuous electric field.

For coupling to the m -th order mode of the overlay, the resonance wavelength (λ_m) can be derived by substituting the phase matching condition into eqs. (1) and (2),

$$\lambda_m = \frac{2\pi d_0 (n_0^2 - n_{\text{ef}}^2)^{\frac{1}{2}}}{m\pi + \varphi_1 + \varphi_2} \quad (3)$$

A fiber-to-PWG coupler has a polarization dependence property because the TE and TM polarizations have different boundary conditions. To measure the characteristics of the sensor, either the TE or TM response can be used. However, an optical device is needed for operating independence of polarization. Two methods can be used to avoid this polarization dependence. The first is minimizing the phase shift (φ_i) using the symmetric structure of the PWG, while the other is maximizing the mode order (m) through a thick PWG. If the refractive index of the upper clad on the PWG is equal to the refractive index of the fiber, φ_i approaches 0 and the dependence of polarization is avoided.⁽⁸⁾ Therefore, when the PWG has a symmetric structure, φ_i of eq. (1) can be negligible, thereby yielding the following simple equation:

$$\lambda_m = \frac{2d_0 (n_0^2 - n_{\text{ef}}^2)^{\frac{1}{2}}}{m} \quad (4)$$

For uniaxial tension, the variation in the refractive index due to compressive stress can be expressed as in eq. (5). This refractive index variation causes the resonance wavelength to shift according to eq. (4).

For polymer materials, the retractive stress is directly proportional to the degree of orientation, which in turn is directly proportional to the birefringence. Thus for uniaxial tension, the birefringence and the refractive stress are related by the single equation.

$$\Delta n = n_{\parallel} - n_{\perp} = C \cdot \sigma \quad (5)$$

Here, n and σ are refractive index and stress applied to the sensor respectively, and C is the stress optical coefficient. The stress optical coefficient of polystyrene is 10 brewsters at room temperature. The value of C depends on the chemical structure of overlay polymers.

$$C = \frac{2\pi(\alpha_{\parallel} - \alpha_{\perp})}{45} \cdot \frac{(n^2 + 2)^2}{nKT} \quad (6)$$

Here, $\alpha_{\parallel} - \alpha_{\perp}$ is the difference in polarizability of a polymer segment parallel and perpendicular to the direction of the chain.⁽⁹⁾ Birefringence is proportional to refractive stress s . When compressive uniaxial stress σ is applied to the superstrate of the sensor, stress birefringence (photoelasticity) is introduced into the sensor because overlay polymers are optically sensitive to stress.

When pressure was applied to the proposed sensor, the effective refractive index of the PWG mode changed according to the stress optical coefficients of the waveguiding polymers. Variations in the applied pressure were detected using the shift in the resonant wavelength resulting from the effective refractive index variation of the PWG, thereby demonstrating the efficacy of the device as a pressure sensor.

3. Materials and Methods

The proposed sensor is composed of a side-polished single mode fiber and a multimode PWG. Figure 2 shows the fabrication procedure of the sensor device.

Optical fibers located inside curved V grooves with a 15 cm bending radius (R) were formed on silicon wafers using the potassium hydroxide (KOH) anisotropic etching technique.⁽¹⁰⁾ The jacket-removed single mode fibers were glued onto the grooves using an adhesive epoxy, then the fibers were polished using #1000 μm and #8000 μm polishing powders on polishing pads consecutively. The thickness of the remaining fiber clad (g_0) was monitored using the liquid drop method⁽¹¹⁾ where g_0 is calculated based on the radiation coupling loss resulting from a high index liquid being dropped on the polished fiber surface. The PWG was fabricated by a spin-coating method on a side-polished fiber block. Three polymers such as AZ1512 (Hoechst, lift off photoresist), polystyrene (Aldrich) and THB-30 (Japan synthetic rubber, negative photoresist), were selected as the materials for the PWG. The SiO_2 layer on the PWG was prepared using RF sputtering (thickness, 500 nm).

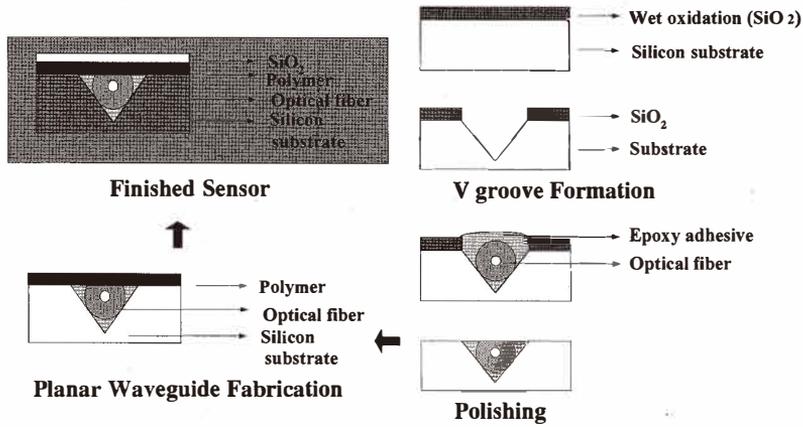


Fig. 2. Fabrication procedure for pressure sensor.

Figure 3 shows the SEM photograph of a silicon V-groove (a) and the cross-sectional view of a polished fiber block (b).

The optical alignment for measuring the wavelength responses of the fabricated sensor consisted of a white light source (Ando, AQ-43038), an optical spectrum analyzer (HP, 86140A), a modified uniaxial compression device, and an XYZ translation stage, as shown in Fig. 4.

The uniaxial compression device was modified to measure the applied pressure, determined as the uniaxially uniform load acting on a unit area of the prepared sensor. The stress was applied on silicon pad (3 mm × 3 mm) which was fixed beneath the metal ring of the uniaxial compression device in order to apply uniform pressure. The stress-loaded area on the waveguide surface is less 160 μm × 300 μm as shown in Fig. 3. Therefore, the uniform stress is applied along the polymer waveguide propagation length because the stress-loaded area is much wider than the evanescent field coupling area.

The value of the displacement gauge at the center of the metal proving ring increases in proportion to the load applied to the sensor device. As such, the load acting on the sensor is the metal ring's elastic constant multiplied by the gauge's displacement. Therefore, the calculated applied pressure can be expressed as in eq. (7).

$$\text{Stress}(\sigma) = \frac{\text{load}}{\text{unit area}} = \frac{C_r \cdot d}{A} \tag{ 7 }$$

Here, C_r is the mean load calibration (ring's elastic constant) of the metal proving ring, d is the displacement of the gauge at the center of the metal proving ring, and A is the unit area of the manufactured sensor.⁽¹²⁾

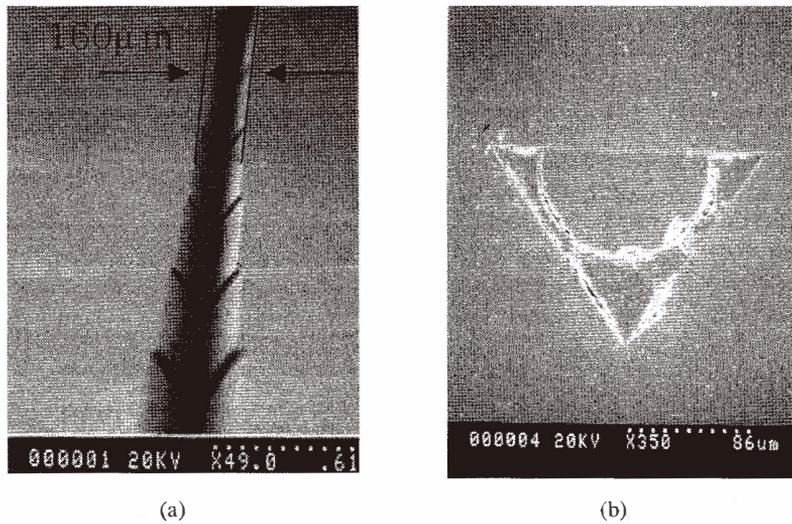


Fig. 3. SEM photograph and cross-sectional view of manufactured sensor. (a) SEM photograph of silicon V-groove, (b) cross-sectional view of a polished fiber block.

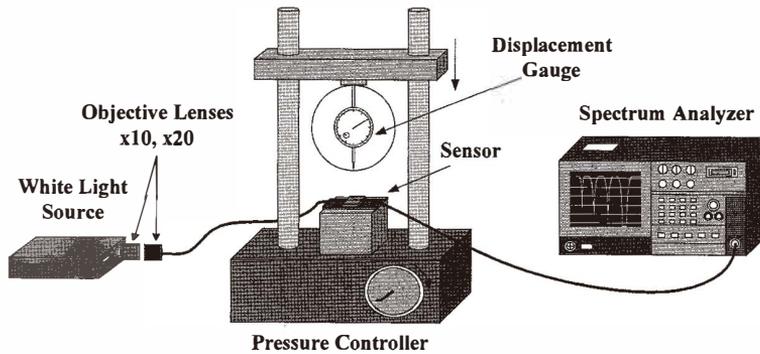


Fig. 4. Experimental setup for pressure measurement of prepared sensor.

4. Results and Discussion

The polarization dependence of the fiber-to-PWG coupler was investigated prior to the pressure measurement of the sensor. Figures 5(a)–5(c) show the spectral response of the TE and TM polarization of the coupler based on the material used on the PWG.

The phase shift ($\Delta\lambda$) between TE and TM mode at minimum resonant wavelength are within 2 nm when SiO₂ was used as the upper-clad layer as shown in Fig. 5(c). The results

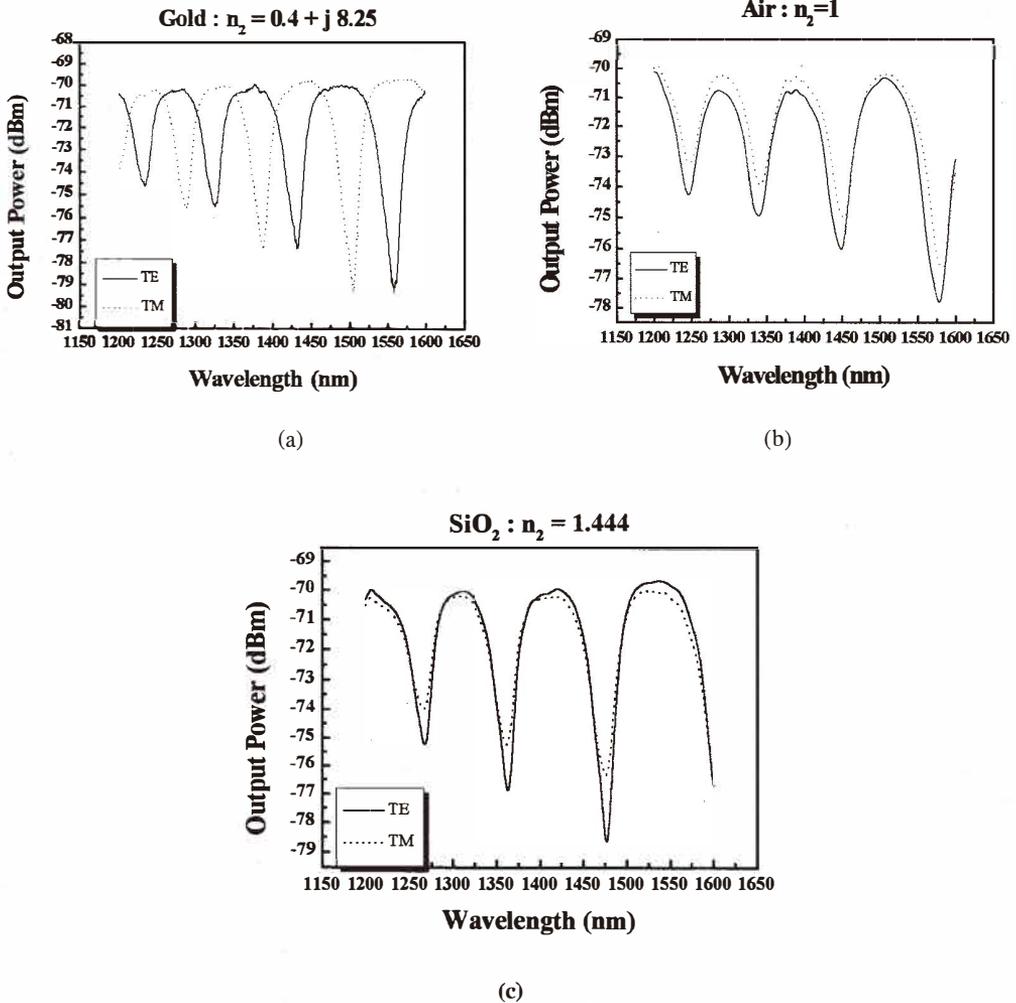


Fig. 5. Polarizing responses for different cladding materials (a) $n_2=0.4+j8.25$ (gold), (b) $n_2=1.0$ (air), (c) $n_2=1.444$ (SiO_2).

show that the dependent polarization was eliminated by the symmetric structure of the PWG; i.e., when a material with a refractive index equal to that of the fiber clad was used as the upper clad on the PWG. These results suggest a decreased phase shift at the top and bottom boundaries of a PWG with a symmetric structure. Figure 6 shows the dispersion curve of a planar waveguide as a function of waveguide thickness when SiO_2 is used as the upper clad material to form a symmetric structure in order to eliminate polarization

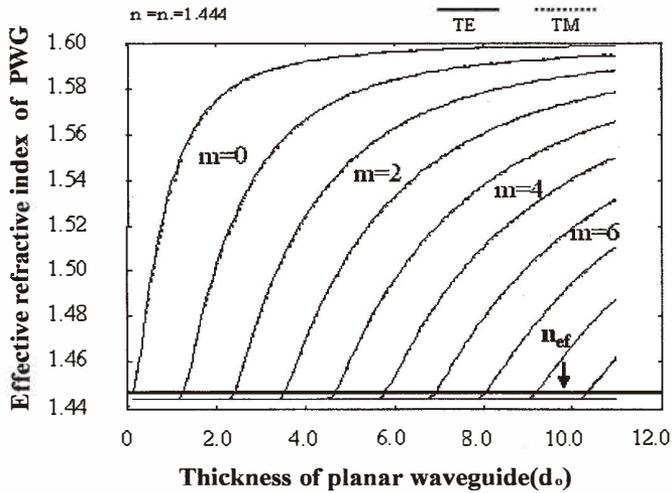


Fig. 6. Dispersion curve of a planar waveguide as a function of planar waveguide thickness (μm) ($\lambda = 1.55 \mu\text{m}$, $n_c = 1.60$, $n_1 = n_2 = 1.444$ (symmetric planar waveguide, upper-clad material: SiO_2)).

dependence. The waveguide thickness and effective refractive index are chosen as the variables of device structures. The effective refractive index of PWG is changed with the variation of planar waveguide thickness. It is also shown that there is no difference of effective refractive index (structural birefringence) between TE and TM modes because of the symmetric structure of the waveguide. The experimental results shown in Fig. 5 also concur with this theory. Considering this effect, the fabricated sensors were coated with SiO_2 .

The wavelength response of the coupler relative to the PWG thickness is shown in Figs. 7(a)–7(c), where the number of coupling modes increases as the thickness of the PWG increases; meanwhile, the bandwidth of the resonance wavelength diminishes as the gap between the wavelengths decreases. This result indicates that thickening the PWG can be used to improve the resolution of the sensor.

The influence of the residual fiber clad thickness (g_c) of the coupler was also measured. The experimental results are shown in Fig. 8, where a decrease in the residual fiber clad thickness produced a broader bandwidth and greater coupling depth. Therefore, the residual fiber clad thickness of the fabricated sensor can be properly controlled using the bandwidth and coupling depth.

Figures 9 (a)–9(c) show the resonance wavelength responses of the prepared pressure sensor relative to variation in the pressure at room temperature (25°C) when AZ1512, polystyrene, and THB-30 were used as the PWG materials.

The shifts in the center wavelength were 0.033 nm/bar , 0.024 nm/bar , and 0.16 nm/bar when the light-guiding polymers were AZ1512, polystyrene, and THB-30, respectively. The measurement ranges are from 0 to 300 bars. The three polymers used as PWG

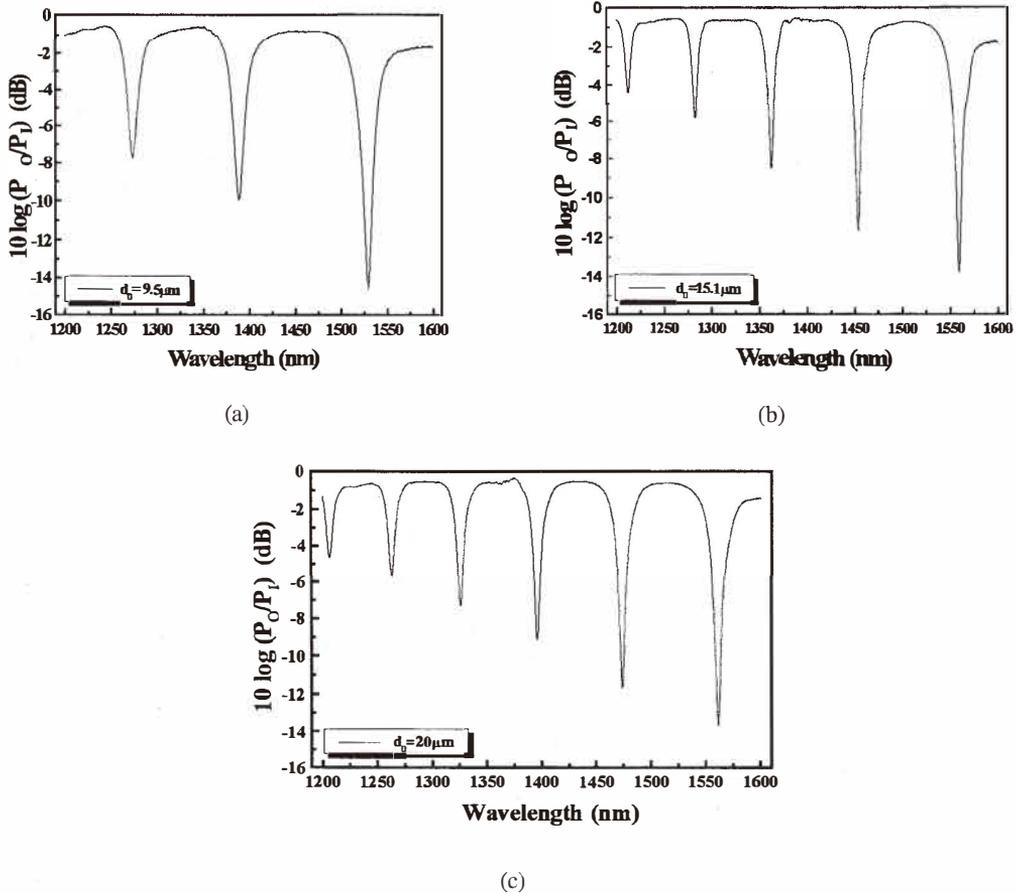


Fig. 7. Wavelength responses when thickness of planar waveguide was changed.

materials exhibited different sensitivities according to their own different stress optical coefficients.

Figure 10 shows the resonance wavelength shift relative to the applied pressure. Changing the material of the PWG altered the characteristic of the sensor, plus the moving distances of each resonant wavelength from the initial point were found to be proportional to the pressure.

One of the statistical methods to define sensors linearity is the correlation factor. The range of correlation value is from -1 to 1 . If it is 1 , the sensitivity is completely linear with positive gradient and if it is -1 , it is negatively linear. When THB-30, AZ1512 and polystyrene are used as a planar waveguide, the correlation factors are 0.9947 , 0.9983 and 0.9914 , respectively, which indicates that the sensitivities are very linear in three waveguide polymers.

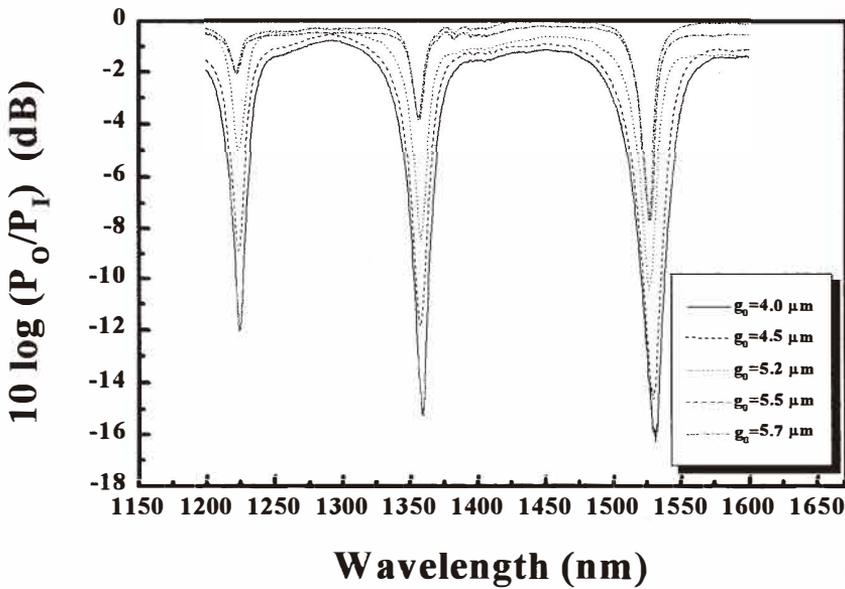


Fig. 8. Transmittance spectrum relative to coupling gap (g_0), upper clad material: SiO_2 .

The maximum pressure to maintain good linearity is 300 bars in all three polymers. The sensor sensitivity is not linear over 300 bars and sensor devices are broken over 350 bars. Therefore the linearity correlation was calculated under 300 bars. But, we estimate this pressure sensor can measure over 500 bars because the optical fiber and fiber core are normal after the device is broken. Only the silicon used as fixing block was broken.

These experimental results indicate that the sensitivity varied depending on the PWG polymer. In reality, when THB-30 was employed as the PWG material, the sensitivity was about seven times higher than that with polystyrene. As such, the proposed pressure sensor can measure high pressure, plus linear wide-range sensing is possible from 0 to over 500 bars. Accordingly, with the proposed sensor, sensitivity and spectral displacements can be controlled by using a different PWG material with a different stress optical coefficient, thereby enabling the measurement of various pressures.

5. Conclusion

A pressure sensor was presented that uses the resonant wavelength shift of a single mode fiber-to-PWG coupler relative to pressure variations. Sensor design techniques to reduce the polarization dependent property and change the pressure sensitivity were also presented. The characteristics of the fabricated sensors confirmed the theoretical prediction, and exhibited a high measurement capability with various sensitivities and good linearity. It was also demonstrated that the proposed wavelength-based method enables the

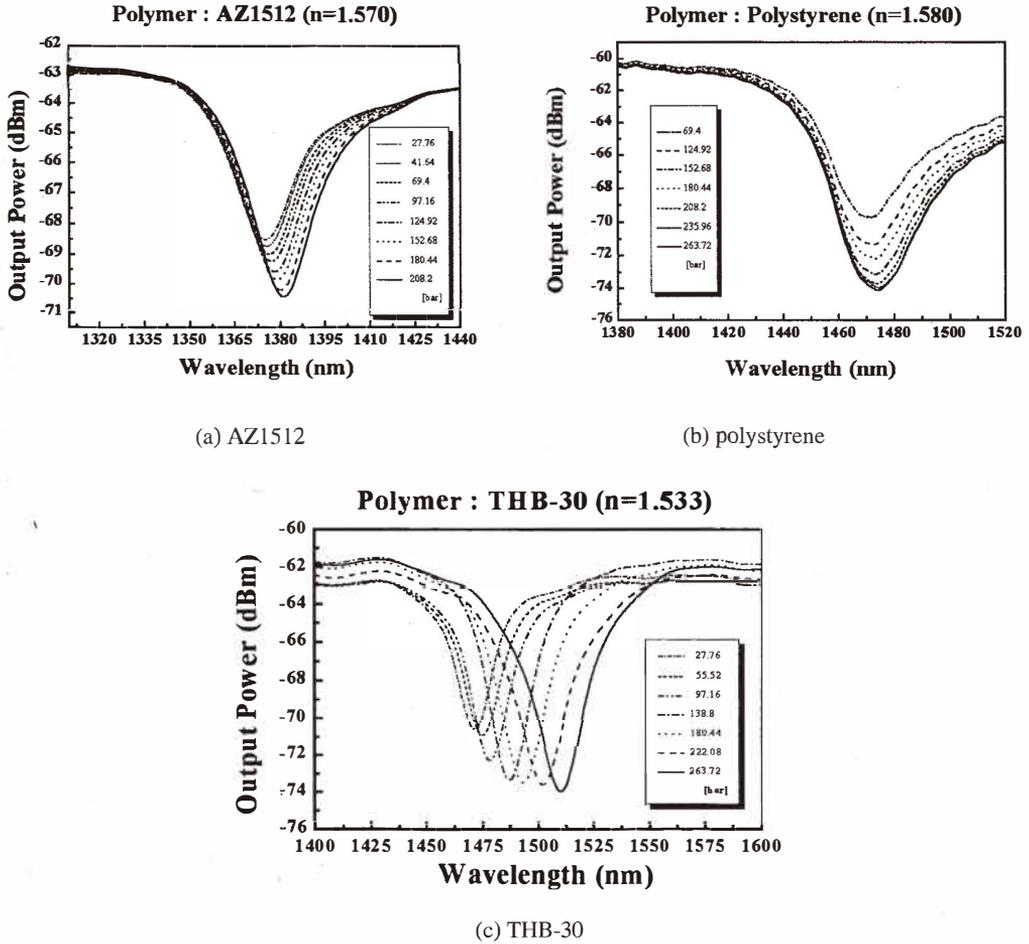


Fig. 9. Wavelength responses of prepared pressure sensor with variation in pressure at room temperature (25°C), when AZ1512 (a), polystyrene (b), and THB-30 (c) were used as PWG materials.

stress-optical coefficient of the overlay materials to be determined indirectly because the sensitivities are different according to the polymers used as waveguides. With the proposed pressure sensor, sensitivity and spectral displacements can be controlled by changing the PWG material, thus a better performance and variety of applications are anticipated if a polymer with an excellent pressure optic property is used as the PWG. An approximated stress optical coefficient of the employed PWG material can be obtained by observing the resonant wavelength shift relative to a variation in pressure. In future studies, the effect of the structural and chemical characteristics of the polymers used on the

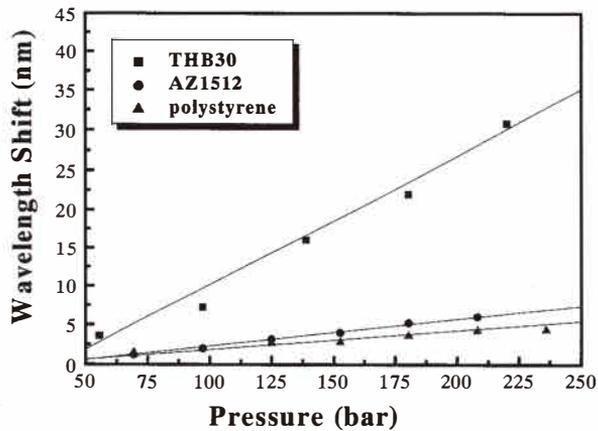


Fig. 10. Sensitivity variation of sensor relative to planar waveguide materials.

wavelength movement and refractive index change according to pressure variations will be investigated. In addition, further research on various PWG materials such as PVDF/TrFE with piezo-optic properties and PWG polymers will be conducted.

References

- 1 K. McCallion, W. Johnstone and G. Fawcett: *J. Optics Letters* **8** (1994) 542.
- 2 S. G. Lee, J. P. Sokoloff, B. P. McGinnis and H. Sasabe: *J. Optics Letters* **9** (1997) 606.
- 3 A. Gloag, N. Langford, K. McCallion and W. Johnstone: *J. Optics Letters* **11** (1994) 801.
- 4 W. Johnstone, S. Murray, G. Thursby, M. Gill, A. McDonach, D. Moodie and B. Culshaw: *J. Electron. Letters* **27** (1991) 894.
- 5 A. D. Kersey, T. A. Berkoff and W. W. Morey: *J. Electron. Letters* **28** (1992) 236.
- 6 H. J. Bae, S. H. Son and S. Y. Choi: *J. Korean Sensor Society* **10** (2001) 148.
- 7 W. Johnstone, G. Thursby, D. Moodie, and K. McCallion: *J. Optics Letters* **17** (1992) 1538.
- 8 K. T. Kim, H. W. Kwon, J. W. Song, S. J. Lee, W. G. Jung and S. W. Kang: *J. Optics Communications* **180** (2000) 37.
- 9 D. W. Van Krevelin: *Properties of Polymer* (Elsevier Sci. Publishing Co., New York, 1990) Chap. 10. (299).
- 10 S. M. Tseng and C. L. Chen: *J. Applied Optics* **31** (1992) 3438.
- 11 S. P. Ma and S. M. Tseng: *IEEE J. of Lightwave Tech.* **15** (1995) 864.
- 12 K. H. Head: *Manual of Soil Laboratory Testing*, Vol. 2 (John Wiley and Sons Inc., New York - Toronto, 1994) Chap. 13 (292).