

The Evanescent Wave Birefringence Change in a Polymer Optical Waveguide with High Refractive Index Layers of Nanometer Scale Thickness for Optical Sensing

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Accepted 20 April 2009

Abstract

We investigate the optical birefringence properties of evanescent field excited in the polymer waveguide where local engineering of refractive index is applied for evanescent mode enhancement for optical sensor purpose. Additional cladding layers of nanometer scale thickness comprising high index materials such as TiO_2 , SiO_2 and their combination are deposited to enhance the evanescent mode interaction with the analyte solution on the waveguide sensing surface. We perform the measurement of the time-dependent polarization change caused by analyte solution injection and demonstrated that the device differential sensitivity stemming from analyte-induced birefringence change increases with increasing evanescent mode interaction with analyte. It is also seen that the analyte layer formation over a long term period can induce an additional birefringence change even in the case of no concentration change of analyte solution. The temporal response of evanescent mode

birefringence change is also discussed using the different types of analyte solutions for the cases of deposition of various high-index materials on the waveguide.

Keywords: Optical sensing, Evanescent wave, Optical polarization, Refractive index, Nanometer thickness cladding

Introduction

Optical waveguides have been exploited as optical-sensing transducers for label-free bio-chemical sensors due to a number of advantages including real-time detection and capability of on-demand sensitivity engineering. Moreover, integrated optical transducers that involve dielectric waveguides are expected to find many applications for small-sized, relatively robust optical sensors. In particular, Mach-Zehnder interferometer (MZI) scheme was utilized for optical sensors, where analyte of concern was adsorbed onto the sensing surface on which evanescent field experienced refractive index variation¹⁻⁴. However, a MZI scheme has drawbacks of limited coupling efficiency of recombination at the interferometer output and unavoidable polarization impurities enhanced by inherent device birefringence.

On the other hand, single-waveguide sensors can be made by employing optical birefringence of evanescent field interacting with target analyte⁵⁻⁸. The phase retardation between two orthogonal polarizations into which a sensor input polarization is decomposed, is generated by analyte adsorbed onto the sensing surface of a single waveguide, leading to the polarization change that can be converted to intensity modulation through a polarizer at the signal detection. In comparison with a MZI scheme, a birefringence scheme allows compact structure for multi-channel sensing transducers and is free of noise source that is present in a MZI scheme due to the incoherence between external disturbances affecting both-arms effective path-length of the interferometer. On the other hand, the use of a single optical path for optical birefringence transducer ensures little effects of external noise found in a MZI scheme, and allows compact structure of optical sensors.

In this work, we investigate optical birefringence

change for a single waveguide sensor where analyte-induced birefringence occurs for a signal transducing. High-refractive index material such as TiO_2 is deposited as a sensing surface on a polymer waveguide to see sensitivity changes. The time-dependent response of the waveguide device is measured when the analyte solution whose concentration varies continuously is set to flow on the sensing surface. It is estimated that the higher sensitivity results from the higher fraction of evanescent mode energy which is found in the case with deposition of TiO_2 only, compared to those of the cases of the SiO_2 deposition or SiO_2 - TiO_2 deposition. In addition, we also discuss noise-like transients of device response at analyte injection for the better estimation of the device sensitivity.

Results and Discussion

Let us introduce the Jones column vectors describing a polarization state at an waveguide input as given by

$$\mathbf{P}_{\text{in}} = \begin{bmatrix} \Psi_{\text{TE}} \\ \Psi_{\text{TM}} \end{bmatrix} \quad (1)$$

where $\Psi_{\text{TE/TM}}$ represents the optical field amplitude along the TE/TM polarization (transverse electric (TE) or transverse magnetic (TM)). Then the polarization at the waveguide output is given by

$$\mathbf{P}_{\text{out}} = \begin{bmatrix} e^{-i\Gamma/2} & 0 \\ 0 & e^{+i\Gamma/2} \end{bmatrix} \begin{bmatrix} \Psi_{\text{TE}} \\ \Psi_{\text{TM}} \end{bmatrix} \quad (2)$$

where Γ is the relative phase difference (phase retardation) between the two orthogonal polarizations. Phase retardation is caused by index mismatching between the two polarizations, which is present in a birefringent material. Moreover, this phase retardation can be modified by an effective refractive index change resulting from evanescent wave interaction with analyte adsorbed on the sensing surface as given by

$$\Delta\Gamma = \frac{2\pi}{\lambda} (\Delta n_{\text{eff}}^{\text{TE}} - \Delta n_{\text{eff}}^{\text{TM}}) \quad (3)$$

where $\Delta n_{\text{eff}}^{\text{TE/TM}}$ is the effective refractive index change of the waveguide propagation mode for TE/TM polarization and λ is the wavelength in use. Thus, output polarization change induced by analytes can be detected through a polarizer as an intensity change. Meanwhile, the sensitivity of the waveguide devices that use evanescent wave for analyte sensing can be given by⁷

$$S_{\text{TE/TM}} = \frac{\Delta n_{\text{eff}}^{\text{TE/TM}}}{\Delta n_s} \quad (4)$$

where Δn_s is the refractive index change by analyte in

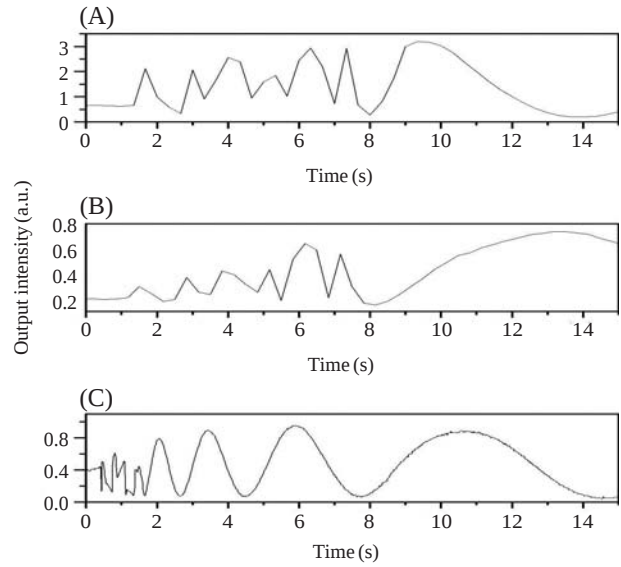


Figure 1. Polarization change measurement with water as a function of time. (A): a polymer waveguide with no deposition on its top, (B): a polymer waveguide with deposition of an 100 nm thick SiO_2 layer on its top, (C): a polymer waveguide with deposition of a 20 nm thick TiO_2 layer on it top.

the sensing region. Here Δn_s is assumed to be approximately polarization-independent. Then, the sensitivity for each orthogonal polarization can determine the differential sensitivity, which is proportional to the $\Delta\Gamma$, as given by⁷

$$\Delta S = S_{\text{TE}} - S_{\text{TM}} = \frac{\lambda \Delta\Gamma}{2\pi \Delta n_s} \quad (5)$$

First, the water sensing measurement is performed as shown in Figure 1(A) for the cases of no deposition of additional layer on the polymer waveguide, an 100 nm thick SiO_2 layer deposition in Figure 1(B), and a 20 nm thick TiO_2 layer deposition in Figure 1(C). Little enhancement of the device sensitivity is seen in the case of Figure 1(B) compared to Figure 1(A), while significantly improved oscillatory behavior is observed after the initial transients of signals in the case of Figure 1(C), compared to Figure 1(A) and (B). The fact that the TiO_2 deposition improves oscillation number of signals, leads us to believe the TiO_2 induced-enhancement of evanescent mode interacting with water. However, the fact that water concentration maintains invariant ensures no additional refractive index change over the oscillation period in Figure 1(C). Consequently, we can infer that this oscillatory behavior can be due to the formation of water films accumulated over the long term period under the same concentration of analyte (water).

The effects of a 20 nm thick TiO_2 layer deposition

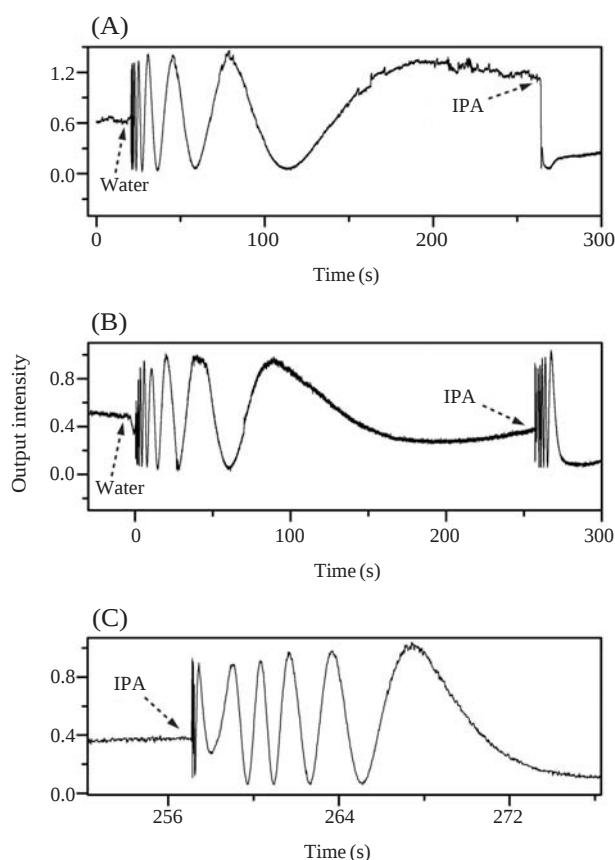


Figure 2. Polarization change measurement with water and IPA as a function of time. (A): a polymer waveguide with no deposition on its top, (B): a polymer waveguide with a 20 nm thick TiO_2 layer deposition on its top, (C): a magnified view of (B) for IPA case.

on the device sensitivity can also be seen when IPA (Isopropanol)/water solution is used as an analyte. As shown in Figure 2(A), about half-period of an oscillation in the output intensity through a polarizer, corresponding to π phase-retardation, is obtained in the case with no deposition of high-index material, whereas a number of oscillations are achieved in the case with a 20 nm TiO_2 layer deposition as shown in Figure 2(B). However, the noise-like initial transients of the device response that occurs concomitantly with analyte injection leads to a difficulty in estimating the number of signal oscillations, and thus, an uncertainty in estimating the ΔS of the waveguide device in the cases of sensing either water or IPA.

It is found that such an ambiguity in ΔS estimation can, however, be improved by using glycerol solution as the analyte. Figure 3(A)-(D) show the measurement with glycerol solution for the different types of high-index materials deposited on a polymer waveguide. As shown in Figure 5, 10 mL glycerol is pumped to

Table 1. Relation between the differential sensitivity ΔS and the fraction of evanescent field power for TE and TM polarizations.

Waveguide (W.G.) type	ΔS	F_{TE}	F_{TM}
$\text{SiO}_2/\text{polymer W.G.}$	1.4×10^{-3}	0.30%	0.26%
$\text{TiO}_2/\text{SiO}_2/\text{polymer W.G.}$	3.7×10^{-3}	1.9%	0.40%
$\text{TiO}_2/\text{polymer W.G.}$	7.4×10^{-3}	2.2%	0.44%

be injected from the beaker to the mixer which is pre-filled with 80 mL water. A polymer waveguide with no deposition on top of it exhibits noise-like signal only, shown in Figure 3(A), but an 100 nm thick SiO_2 layer deposition enables injected glycerol solution to cause birefringence change as shown in Figure 3(B), resulting in about half-oscillation of the output intensity through a polarizer. In addition, an approximate single oscillation of the signal, which corresponds to 2π phase-retardation, is seen in the case of deposition of a 20 nm thick TiO_2 layer on top of an 100 nm thick SiO_2 layer deposited on a polymer waveguide, as shown in Figure 3(C). Further increase in the number of oscillations is observed in the case of a 20 nm thick TiO_2 layer deposited on a polymer waveguide, as shown in Figure 3(D). The inset of Figure 3(D) shows the case with 20 mL glycerol injection, producing about four oscillations of the signal, and this corresponds to almost twice the number of oscillations in the case of 10 mL glycerol.

The use of glycerol renders the sensing device relatively free of noise-like transients of the signal compared to the case of using IPA. This may be attributed to higher hydrophilicity of glycerol molecules than that of IPA molecules, eliminating the dynamic features of noise that can be engendered instantaneously by the analyte solution injection.

Table 1 shows the ΔS estimated from the measurement based on Figure 3(A)-(D). Here, F_{TE} and F_{TM} are the calculated fractions of evanescent field power out of the whole power of light propagating the waveguide for TE and TM polarizations, respectively. Assuming the phase of incident light is optimized, these differential sensitivities of the centimeter long device, approximately correspond to the one tenth of those of a conventional (bulky) surface plasmon resonance (SPR) device. As illustrated in Figure 3(A)-(D) and Table 1, the increase in the number of oscillations due to the deposition of higher-index materials on a polymer waveguide leads the ΔS to increase, indicating the enhancement of evanescent mode interacting with analyte solutions on the sensing surface. This is in agreement with the calculation of the fraction of evanescent mode power.

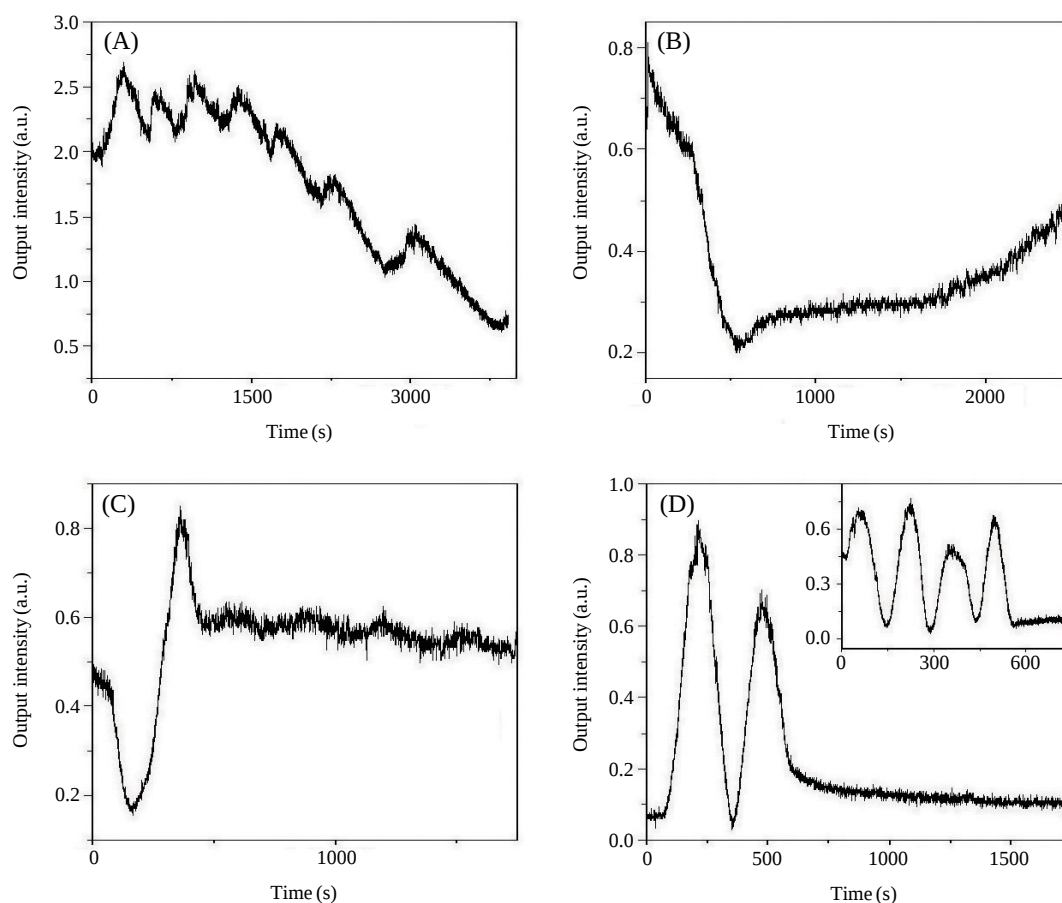


Figure 3. Polarization change measurement with 10 mL Glycerol (mixed with 80 mL water) as a function of time. (A): a polymer waveguide with no deposition on its top, (B): deposition of an 100 nm thick SiO_2 layer, (C): deposition of a 20 nm thick TiO_2 layer on top of an 100 nm thick SiO_2 layer, (D): deposition of a 20 nm thick TiO_2 layer.

Conclusions

We investigate optical birefringence change of a single polymer waveguide for an optical sensor purpose, with its refractive index engineered to enhance the fraction of energy of evanescent field that interacts with target analytes. The deposition of the different types of high-index material is performed on top of the channel waveguide with an aim of obtaining different degree of birefringence change induced by analytes on top of the device.

Both the birefringence measurements and our calculation indicate that higher device-sensitivity arises from higher fraction of evanescent mode energy, leading us to choose the deposition of TiO_2 only as an additional cladding layer on the polymer channel waveguide. It is also seen that long-term period birefringence change can occur even in the absence of analyte solution concentration change, due to the analyte layer

formation as checked in the measurement with water only.

Lastly, this work can be extended by examining external perturbation effects on two kinds of waveguide sensor devices, i.e., a birefringence scheme (a single waveguide), and a MZI scheme (a pair of waveguides), which allows comparison in noise features between both schemes.

Materials and Methods

Our birefringence-change-sensing device is based on a polymer channel waveguide fabricated as follows: polymer ZPU 12-450 (cladding) is spin-coated (700 rpm/30 s) on a Si-substrate before UV curing and baking. Then photolithography is utilized to form a straight line pattern of photo-resist (PR) with the following deposition of a TiO_2 thin film except the patterned line. The patterned PR line is then etched off, follow-

ed by dry etching of the underlying polymer along the patterned line using NLD O_2 plasma. Then, the patterned TiO_2 is removed and the subsequent coating and additional dry etching of polymer ZPU 13-460 (core) provides a polymer channel waveguide of 7 μm width and 2 μm thickness.

For the enhancement of evanescent mode energy fraction, TiO_2 is deposited through a 2 cm hollow gap of an Aluminum mask installed 2.5 mm above the waveguide cladding. This gives deposition of a 20 nm thick TiO_2 film whose thickness tapers off towards the mask shadow along the waveguide direction⁷, as shown in Figure 4. The tapered thickness of TiO_2 produces adiabatic coupling of light to enhance evanescent mode without substantial propagation loss.

Care was taken in choosing the thickness of a TiO_2 layer to ensure a single-mode propagation for both TE and TM polarizations without a loss of substantial enhancement of evanescent mode.

Instead of a 20 nm thick TiO_2 layer deposition mentioned above, the different types of high-index materials are deposited on top of a polymer waveguide: (1)

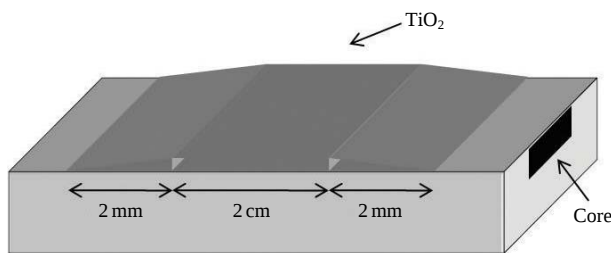


Figure 4. Schematic of a polymer channel waveguide on top of which TiO_2 is deposited.

an 100 nm thick SiO_2 layer, (2) a 20 nm thick TiO_2 layer below which an 100 nm thick SiO_2 layer is deposited. This allows comparison between the different types of high-index material deposition in terms of the device sensitivity.

Figure 5 shows schematic of an experimental setup to detect the temporal response of the waveguide device to the adsorption of analyte solution whose concentration continues to change. A diode laser is used as an optical source emitting continuous laser at 1,064 nm where light absorption in water is found to be weaker than at other wavelengths. Incident polarization is adjusted at 45 degrees with respect to the waveguide layers and microscope-objective lenses (OL) are used for in- and out-coupling of light. A polarizer (P) is placed before a photodiode to convert the polarization change to light intensity change.

The analytes used to verify the characteristics of the waveguide device are water, glycerol/water solution, and IPA/water solution. The analyte in a solution format is set to continue to flow on the waveguide sensing surface, avoiding substantially non-uniform spreading of the analyte solution on the sensing surface at the analyte injection. Analytes such as pure glycerol and pure IPA are driven by the pump 1 to flow from a beaker to the mixer filled with 80 mL water, producing the increase in the concentration of analyte solution. Given the concentration, the rate at which analyte solution is set to flow by the pump 2 on waveguide sensing surface is adjusted to be faster than pump 1, making it possible to detect output polarization change as a function of time, due to the refractive index change caused by the concentration change.

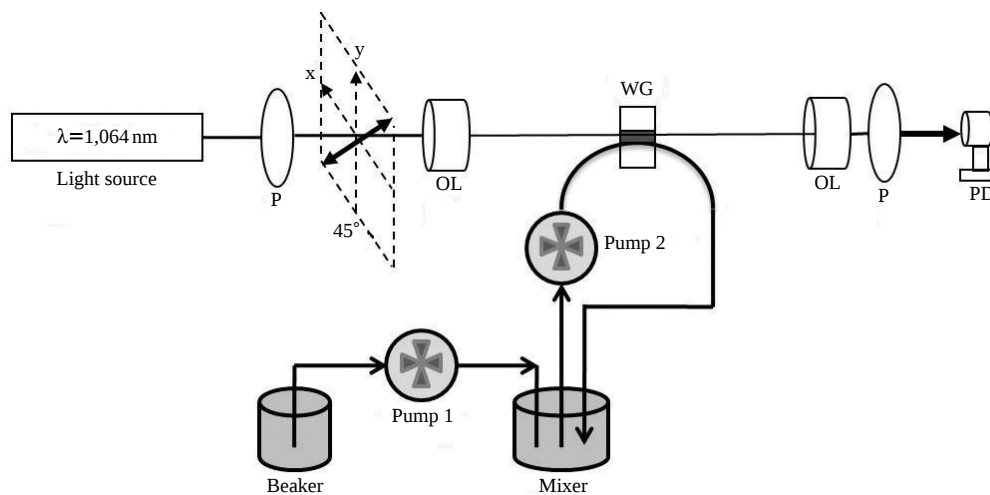


Figure 5. Schematic of an experimental setup for polarization change detection. P: polarizer, OL: objective lens, WG: waveguide, PD: photodiode.

Acknowledgements

This research was supported by the Kyungwon University Research Fund in 2009, and also supported by Ministry of Knowledge Economy (MKE), Korea as a project, "The next generation core technology for Intelligent Information and electronics".

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