Instrumental Achievements

# Lock-in Modulation Detection for a Difference Interferometric Slab Optical-Waveguide Refractive-Index Sensor

**Kin-ichi TSUNODA,† Tomonari UMEMURA, Katsuyuki AIZAWA, Yoshito TAKAHASHI, and Tamao ODAKE**

*Department of Chemistry, Gunma University, Kiryu 376–8515, Japan*

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A difference interferometric refractive-index (RI) sensor is based on the differential phase modulation between the two orthogonal polarization (TE and TM) modes of guided light beams of optical waveguide.[1–4] We have developed such a type of RI sensor using a slab optical waveguide (SOWG) with a prism coupler.[5] This type of RI sensor allows us to use a relatively simple optical configuration, compared with other RI sensors using a planer optical waveguide, such as a Mach–Zehnder interferometer-type sensor.[6,7] However, there are some difficulties concerning the detection system. Although we applied an absorbance detection system to the RI sensor in previous work,[5] its sensitivity was dependent upon the $D_0$ value in Eq. (2) in the Theory section; the $D_0$ value is involved in the coefficient in the expression for the relation between the absorbance and the RI change of the sample solution. The $D_0$ value could change in each experimental setup, and optimization of the measurement conditions was a tedious task.[5] On the other hand, other researchers have used rather complex detection systems to avoid such a problem; multiple photo-detectors systems or a charge-coupled device (CCD) camera system were applied when complicated signal processing was required.[1–4]

In this paper, we describe a simple detection system for the RI sensor using lock-in modulation. This system enables us to easily obtain the optimum measurement conditions. Moreover, its experimental setup is much simpler than those of other works;[1–4] a single-beam configuration can be applied and complicated signal processing is not necessary.

## Theory

Figure 1 shows a schematic diagram of the present system.

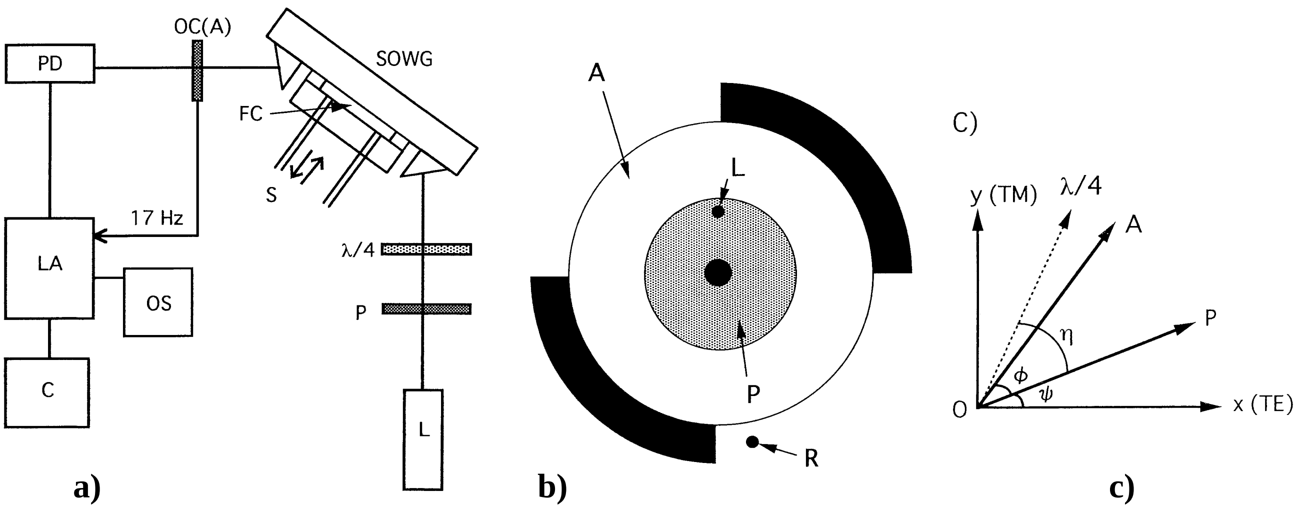


Fig. 1 Schematic diagram of the SOWG RI sensor system with lock-in modulation. a) Arrangement of the sensor system: L, He-Ne laser; P, polarizer P; $\lambda/4$, the $\lambda/4$ phase plate; S, sample solution; FC, flow cell; OC (A), optical chopper (polarizer A); PD, photodiode; LA, lock-in amplifier; OS, oscilloscope; C; computer. b) Schematic diagram of optical chopper (polarizer A): A, transparent plastic sheet; P, polarizer; L, laser light; R, reference light. c) The angles of polarizers P and A and a $\lambda/4$ phase plate on the coordinate of the orthogonal polarization modes TE and TM.

† To whom correspondence should be addressed.
E-mail: tsunoda@chem.gunma-u.ac.jp

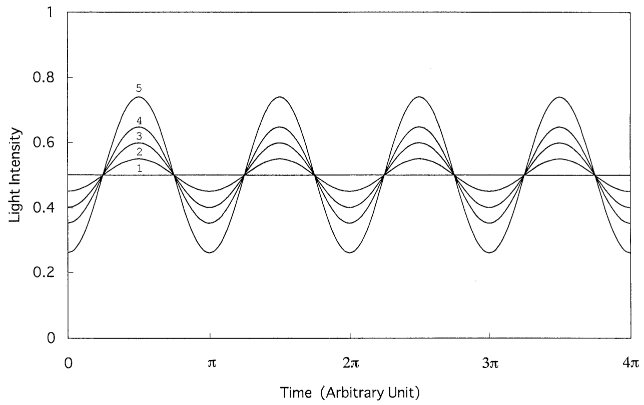


Fig. 2 Simulated sensor response. The phase shift at baseline ($\Delta D$ = 0) was set at $D_0 = \pi/2$. 1, $\Delta D = 0$; 2, $\Delta D = 0.1$; 3, $\Delta D = 0.2$; 4, $\Delta D = 0.3$; 5, $\Delta D = 0.5$ (radian unit).

When an SOWG is used as an absorption cell for liquid samples in a flow cell, $L_{\mathrm{eff}}$ is defined as the effective cell length. According to a textbook on evanescent spectroscopy, $L_{\mathrm{eff}}^{\mathrm{TM}}$ is known to be longer than $L_{\mathrm{eff}}^{\mathrm{TE}}$. The degree of the difference ($\Delta L_{\mathrm{eff}} = L_{\mathrm{eff}}^{\mathrm{TM}} - L_{\mathrm{eff}}^{\mathrm{TE}}$) depends on the RI parameters of the SOWG. The difference ($\Delta L_{\mathrm{eff}}$) causes a phase shift ($D$) between TE and TM modes; the dependence of the change in the phase shift ($\Delta D$) upon a change in the RI of a sample solution ($\Delta n$) is described by

$$\Delta D = -k_0 \Delta L_{\mathrm{eff}} \Delta n, \tag{1}$$

where $k_0 = 2\pi/\lambda_0$, $\lambda_0$ being the wavelength *in vacuo*. The $\Delta D$ value is detected as the change in the guided light intensity ($I$) by the present system according to

$$I = \cos^2\phi - \sin 2\psi \sin 2(\phi + \psi) \sin^2\left(\frac{D_0 + \Delta D}{2}\right), \tag{2}$$

where $D_0$ is a baseline value for $D$, *i.e.*, the $D$ value when a carrier solution is introduced into the sensor; $\psi$ and $\phi$ are defined in Fig. 1c. When $\psi$ is set to $\pi/4$, based on previous work[5] and polarizer A ($\phi(t)$) is rotated as an optical chopper, eq. (2) can be rewritten as

$$I(t) = \frac{\cos[2\phi(t)] + 1}{2} - \cos[2\phi(t)] \sin^2\left(\frac{D_0 + \Delta D}{2}\right), \tag{3}$$

where $t$ is time. According to Eq. (3), the alternating current (a.c.) fraction in $I(t)$ becomes zero at the baseline ($\Delta D = 0$) when $D_0 = \pi/2$; a further calculation reveals that this condition ($D_0 = \pi/2$) gives the best sensitivity for the $\Delta D$ change. Figure 2 shows the change in $I(t)$ along with the $\Delta D$ changes under this condition. The figure shows that the $\Delta D$ changes, *i.e.*, the RI changes in a sample solution ($\Delta n$), can be monitored by an alternating current (a.c.) signal, *i.e.*, the output signal of a lock-in amplifier. Moreover, the condition $D_0 = \pi/2$, where the output signal of a lock-in amplifier at the baseline becomes minimum, can easily be obtained by rotating a $\lambda/4$ phase plate (Fig. 1a).

## Experimental

*Slab optical waveguide*

A potassium ion-doped glass slab optical waveguide (SOWG) was used throughout the study, which was fabricated by an ion-exchange process on commercial soda-lime slide glasses (S-1214 from Matsunami Glass Inc., Japan) in molten potassium nitrate at 673 K for 30 min.

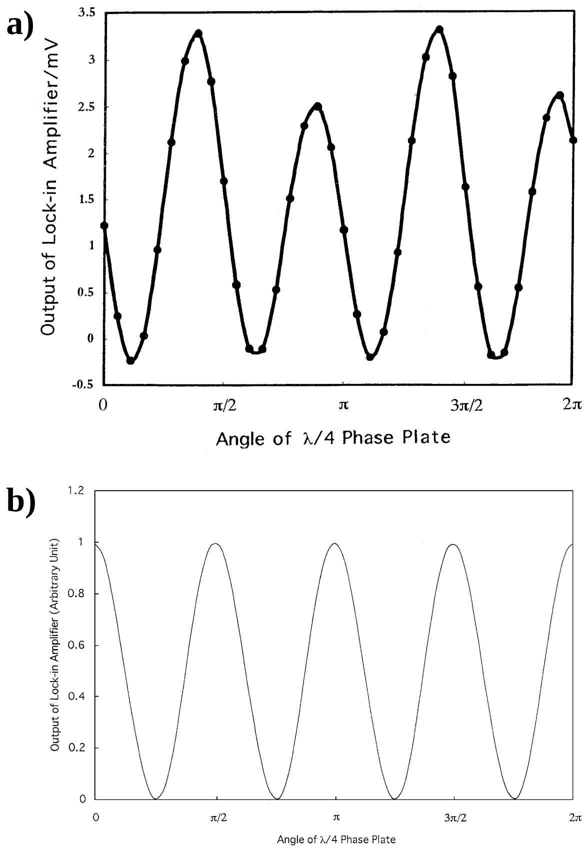


Fig. 3 Dependence of the output signal of the lock-in amplifier at the baseline upon the angle of the $\lambda/4$ phase plate. a) Experimental results. b) Computer simulation.

*Measurement system*

A schematic diagram of the measurement system is shown in Fig. 1a. The SOWG system was basically the same as that described in a previous paper.[5] As shown in the figure, a He-Ne laser (632.8 nm, 2 mW, random polarization) was used as a light source. A polarizer (P) and a $\lambda/4$ phase plate were placed between the SOWG and the light source. A laboratory-made optical chopper (described in Fig. 1b) was placed between the SOWG and a photodiode. The guided light was modulated by the chopper at 17 Hz and detected with the photodiode; the signal was amplified by a 5600A digital lock-in amplifier (NF Circuit Block, Japan) and fed into a personal computer through a general-purpose Interface Bus (GP-IB). The time constant of the lock-in amplifier was set at 0.3 s. The input signal to the lock-in amplifier was monitored with an oscilloscope.

*Measurement procedures*

When deionized water as a carrier was introduced into a flow cell, an a.c. signal on the oscilloscope was monitored. The condition that the a.c. signal became the minimum was selected by rotating the $\lambda/4$ phase plate, which gave the best sensitivity of the sensor response. Then, a sample solution (0.5 $cm^3$) was introduced into the carrier stream *via* a loop injector and the output signal of the lock-in amplifier (mV) was directly monitored on the computer display and stored in the computer.

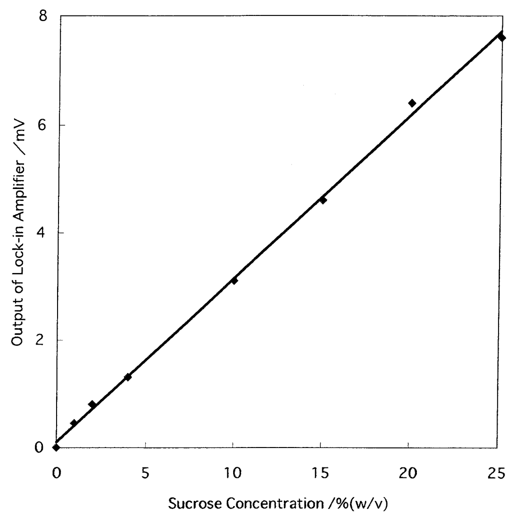


Fig. 4 Calibration curve for sucrose solutions.

Various concentrations of sucrose solutions were used as RI standards.

## Results and Discussion

The present system gave the expected analytical features. Figures 3a and 3b show the results of an experiment and a computer simulation concerning the dependence of the output of the lock-in amplifier upon the angle of the $\lambda/4$ phase plate at the baseline, respectively. As shown in the figures, these results are in good agreement with each other, and the best sensitivity was obtained at those angles giving the minimum output value. Figure 4 shows a calibration curve for sucrose solutions at that condition where the angle of the $\lambda/4$ phase plate was set at 0.17 (radian unit) (see Fig. 3a). The detection limit ($2.2 \times 10^{-4}$ RIU) of the present system was almost the same as that obtained with the absorbance detection ($2.6 \times 10^{-4}$ RIU).

In conclusion, a lock-in modulation detection system was applied for a difference interferometric SOWG RI sensor. The present system is simple in the setup and is easy to operate and to optimize the measurement conditions. Moreover, it will be applicable to an automated measurement system.

### Acknowledgements

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