A Composite Optical Waveguide-Based Polarimetric Interferometer for Chemical and Biological Sensing Applications

Zhi-mei Qi, Kiminori Itoh, *Member, OSA*, Masayuki Murabayashi, and Hiroyuki Yanagi

***Abstract*—A new polarimetric interferometer has been developed on the basis of the phase difference between transverse electric $(TE)_0$ and transverse magnetic $(TM)_0$ modes in a composite optical waveguide (OWG). The composite OWG consists of a single-mode potassium ion-exchanged planar waveguide overlaid with a high-index thin film that has two tapered ends and supports only the TE_0 mode. Applying tapered velocity coupling theory, we found that the TE_0 and TM_0 modes coexisting in the potassium ion-exchanged layer were separated in the thin film region of the composite OWG: the TE_0 mode was coupled into the thin film while the TM_0 mode was confined in the potassium ion-exchanged layer. Interference occurs between TE- and TM-polarized output components when a single output beam is passed through a 45°-polarized analyzer. The phase difference ϕ between both orthogonal output components is very sensitive to the superstrate index n_c in the thin film region. Our experimental results indicate that a slight change of $\Delta n_c = 3.71 \times 10^{-6}$ results in the phase-difference variation of $\Delta\phi = 1^\circ$ for a 5-mm-long TiO_2/K^+ composite OWG with a 34-nm-thick TiO_2 film. Such a simple polarimetric interferometer can be applied to chemical or biological sensors by modifying the upper film surface of the composite OWG with a chemically or biologically active substance.**

***Index Terms*—Chemical and biological sensors, composite optical waveguide (OWG), polarimetric interferometer, tapered velocity coupler, transverse electric $(TE)_0$–transverse magnetic $(TM)_0$ modes splitting and recombination.**

I. INTRODUCTION

AS POWERFUL tools for surface monitoring, optical waveguide (OWG) devices are attracting more and more attention; this is especially the case in light of rapid biotechnological developments and the aggravation caused by environmental pollution [1]–[4]. The use of light and the extension of interaction path render OWG devices highly sensitive, safe, and resistant to electromagnetic disturbances. Optical principles applied to OWG surface monitoring include evanescent absorption, fluorescence quenching, and interferometery. These principles can convert changes in the physical or chemical properties of OWG surfaces due to the interaction with analytes into a measurable intensity signal. Evanescent-absorption and fluorescence-quenching OWG sensors have a limited number of applications because of the limited availability of sensing materials. OWG interferometers are phase-modulated transducers with the ability to respond to changes in refractive index and/or thickness of the sensing layer; they do so by manipulating the effect of evanescent field on the effective index of the guided mode. Almost all of the surface interactions are accompanied with changes in refractive index and/or thickness. Therefore, OWG interferometers can be applied to a variety of chemical or biological sensors by immobilizing different molecule-recognition materials on their surfaces.

It is more difficult to design and fabricate an OWG interferometer than an evanescent-absorption or a fluorescence-quenching OWG sensor. An OWG interferometer requires two beams: one beam is used for sensing and the other is used as a reference. Moreover, both beams should be as close to each other as possible in order to negate the effect of temperature on the device. If the sensing and reference beams of an OWG interferometer are produced by both incident beams, then the device will be difficult to operate. As a matter of fact, both sensing and reference beams of OWG interferometers usually arise from the power splitting of a single incident beam through a Y-junction splitter or via a dual-channel directional coupler. This produces three-dimensional (3-D) OWGs with strict fabrication tolerance. Thus, in contrast to evanescent-absorption or fluorescence-quenching OWG sensors, OWG interferometers rely more heavily on guided-wave theory. A typical OWG interferometer is the Mach–Zehnder device. Although the Mach–Zehnder interferometers (MZIs) are compact, stable, and convenient to use, it is difficult to prepare such devices and therefore their widespread application to surface monitoring is inhibited. From the point of view of surface monitoring technology, it is advantageous to exploit novel OWG interferometers with a low cost, a high sensitivity, and simplicities of fabrication and use.

This paper describes a composite OWG-based polarimetric interferometer. The composite OWG is a dual-layer planar OWG based on tapered velocity coupling theory and has previously been applied to both evanescent absorption-based and surface scattering-based OWG devices [5], [6]. Recently, we discovered transverse electric $(TE)_0$–transverse magnetic $(TM)_0$ mode segregation inside a composite OWGs. Applying this phenomenon, we fabricated an OWG polarimetric interferometer [7]. This new interferometer is very sensitive to various surface changes and could potentially enhance the commercialization of OWG surface monitoring. The composite OWG is inexpensive because slide glass served as the substrate. In addition, combination of a planar structure and the relaxed fabrication tolerance of the tapered velocity

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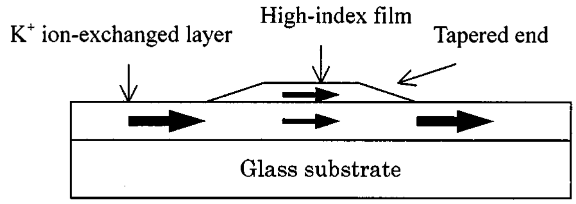

Fig. 1. Schematic diagram of a composite OWG (Arrows represent guided modes)

coupler facilitates the manufacture of composite OWGs. Single incident and output beams make the operation of this new polarimetric interferometer as convenient as the evanescent-absorption sensor. Furthermore, an enhanced evanescent field on the upper film surface of the composite OWG renders it approximately 70 times more sensitive than the conventional Mach–Zehnder device. The following sections present the principle of TE_0–TM_0 mode segregation that occurs inside composite OWGs; an experimental demonstration of the new polarimetric interferometer is included in the report.

II. TE_0–TM_0 Mode Segregation Inside a Composite OWG

The structure of the composite OWG is shown in Fig. 1. It is composed of a potassium ion-exchanged planar OWG overlaid with a high-index thin film that has two tapered ends and supports only the TE_0, mode. The single-mode potassium ion-exchanged OWG plays an important role in the composite OWG for the following reasons:

1) it is a low-loss OWG and allows the guided modes to yield an output light intensity that is enough to be detected after being propagated internally over a long distance;
2) it is a passive OWG and allows a flow cell to be mounted on its surface without disturbing the propagation of guided modes;
3) it has a low index and allows a variety of higher index materials to be used as the thin film of the composite OWG;
4) it is a polarization-insensitive OWG and allows both TE_0 and TM_0 modes to be excited simultaneously by a single beam with a linear polarization.

For the same reason, a single output beam with two orthogonal components corresponding to the TE_0 and TM_0 modes can emerge from the potassium ion-exchanged layer.

As a waveguiding layer, the high-index thin films differ greatly from the potassium ion-exchanged layers in optical properties. The high-index thin films have a large scattering loss and are highly polarization-sensitive because of a large index difference at the superstrate-film and substrate-film interfaces. Fig. 2 shows the calculated cutoff thicknesses of the TE_0 and TM_0 modes, which are a function of the refractive index of the waveguiding layer on the glass substrate. The cutoff thickness of the TM_0 mode is larger than that of TE_0 mode for an isotropic thin film. When the thickness of the upper film of the composite OWG is between the two cutoff values, the TE_0 and TM_0 modes coexisting inside the potassium ion-exchanged

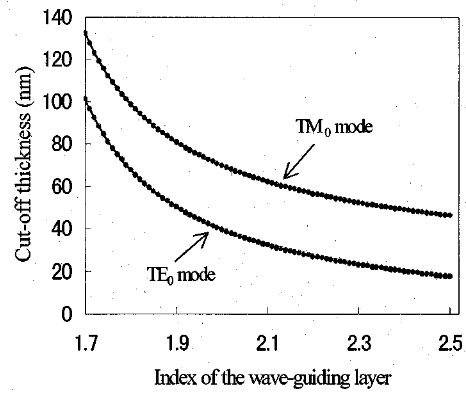

Fig. 2. Calculated cutoff thicknesses of TE_0 and TM_0 modes as a function of the wave-guiding layer index ($\lambda = 633$ nm, $n_s = 1.515$, $n_c = 1.333$).

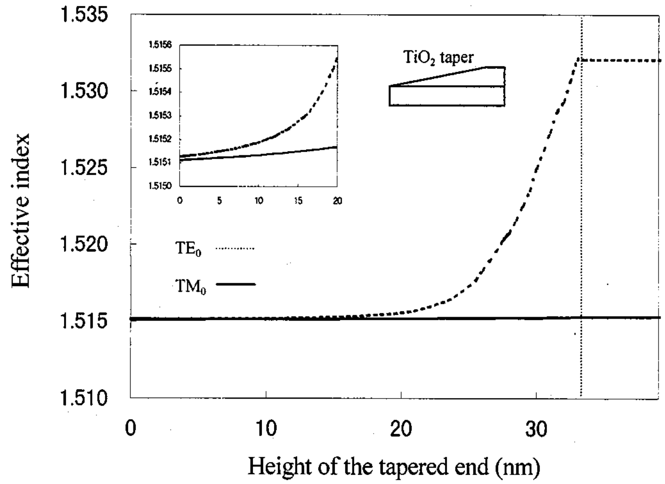

Fig. 3. Calculated effective indexes of TE_0 and TM_0 local modes as a function of the taper height for the TiO_2/K^+ composite OWG ($\lambda = 633$ nm, $n_s = 1.515$ nm, and $n_c = 1.333$). To the right of the dotted line, the TiO_2 film region with a uniform thickness of 34 nm can be seen. Insert shows the effective indexes of both TE_0 and TM_0 modes in the TiO_2 taper region with a height below 20 nm.

layer can be separated in the thin film region by the tapered velocity coupler.

If a guided mode exists inside a waveguiding layer, its effective index, N, must be between the refractive indexes, n_s and n_F, of the substrate and waveguiding layer ($n_s < N < n_F$). According to this requirement, we can judge whether the TE_0 mode is separated from the TM_0 mode inside the composite OWG. We calculated the effective indexes, N_{TE0} and N_{TM0}, of TE_0 and TM_0, local modes inside the TiO_2/K^+ composite OWG. The fabrication and parameters of the TiO_2/K^+ composite OWG were described in Section III-A. The calculation is based on the guided-wave equations for a four-layer OWG composed of a substrate, an ion-exchanged layer, a high-index layer, and a superstrate. As seen in Fig. 3, N_{TE0} increases gradually as the height of the tapered end rises, which is the result of tapered velocity coupling. In the uniform TiO_2 film region (to the right of the dotted line), N_{TE0} is equal to 1.536, which is larger than the index of the potassium ion-exchanged layer (1.52). This finding shows that the TE_0 mode is coupled into the TiO_2 thin film. Because a slight increase in N_{TM0} with a

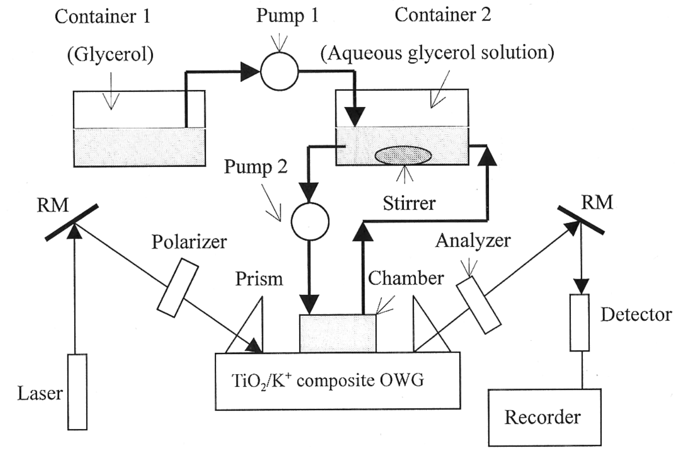

Fig. 4. Experimental set-up of the composite OWG-based polarimetric interferometer used to measure the refractive index of the aqueous glycerol solution

rise in the height of the tapered end, N_{TM0} is below 1.52 in the uniform TiO_2 film region, indicating that TM_0 mode is confined in the potassium ion-exchanged layer. The TE_0 mode entering the TiO_2 thin film has a much stronger evanescent interaction with the analyte than the TM_0 mode. Thus, in contrast to the TM_0 mode, the TE_0 mode can serves as the sensing beam for the new polarimetric interferometer.

III. Experimental Demonstration of the New Polarimetric Interferometer

A. Fabrication of a TiO_2/K^+ Composite OWG

Single-mode potassium ion-exchanged planar OWGs were prepared by dipping soda-lime glass into molten KNO_3 at 400°C for 30 min, TiO_2 thin film was then deposited onto the waveguide by RF sputtering. The prevacuum was 6.5×10^{-3} Pa. The flow ratio of Ar to O_2 was $1:1$ and the sputtering vacuum was kept at 1~1.1 Pa. The sputtering power and duration was 300 W and 5 min, respectively. During sputtering, an Al_2O_3 ceramic mask with a narrow gap mounted at a distance of 2 mm under the substrate gave the thin film of TiO_2 a pattern of 5 mm-wide stripe with two 1-mm-long tapered ends. The ellipsometry measurements showed that the thickness and index of the thin film of TiO_2, were 34 nm and 2.27, respectively. The surface index and exchanged depth of the K^+ ion-exchanged OWG was approximately 1.52 and 2 μm, respectively.

B. Experimental Setup of the New Polarimetric Interferometer

As shown in Fig. 4, two glass prisms were mounted at the ends of the sample as input and output couplers. A flow chamber with a volume of 6.75 mL ($3 \times 1.5 \times 1.5$ cm^3) attached to the middle of the sample shielded the entire thin film of TiO_2 for the measurement of the device's sensing performance. A linearly polarized He–Ne laser beam striking the input prism coupler excited both the TE_0 and TM_0 modes simultaneously in the potassium ion-exchanged layer. A single output beam with two orthogonal components corresponding to the TE_0 and TM_0 modes passed a 45°-polarized analyzer and then reached a photomultiplier used as detector. The interference signal was recorded with a pen recorder connected to the detector. A polarizer located in front of the input prism coupler was used to adjust the intensity ratio between two incident orthogonal components, so as to yield two equal-intensity orthogonal components of the output beam.

C. Theoretical Analysis of the Phase Difference, ϕ

When the TE-polarized output component has the same intensity, I_0, as the TM-polarized output component, the output intensity of the new polarimetric interferometer can be expressed as

$$I = I_0(1 + \cos\phi).$$

The phase difference ϕ between both orthogonal output components is composed of two terms: $\phi = \phi_0 + \Delta\phi$. ϕ_0 is the initial phase difference just before measurement. $\Delta\phi$ is the phase-difference change caused by the interaction of the evanescent field with the analyte during measurement. In case of a known incident wavelength λ and length L of the thin film excluding the two sloping ends, $\Delta\phi$ is a linear function of the difference between the effective index shifts, ΔN_{TE0} and ΔN_{TM0}, of the TE_0 and TM_0 modes in the composite OWG:

$$\Delta\phi = (2\pi/\lambda)L(\Delta N_{\mathrm{TE0}} - \Delta N_{\mathrm{TM0}}).$$

This is an approximate expression because the effect of the tapered ends on $\Delta\phi$ is neglected. In principle, we can derive surface information about the composite OWG at any time. For example, the superstrate index or the thickness and coverage of the adsorbed layer, can be derived from the recorded signal utilizing the guided-wave equation.

D. Performance Measurement of the New Polarimetric Interferometer

We investigated the refractive index-sensing performance of the TiO_2/K^+ composite OWG-based polarimetric interferometer by changing the glycerol concentration of the aqueous solution in the flow chamber (see Fig. 4). Before the experiment, 59.44 g pure water was cycled by pump 2 at a rate of 8 ml/min between container 2 and the flow chamber. After a stable output signal with both equal-intensity orthogonal components was observed, pure glycerol in container 1 was injected into container 2 by pump 1 at a rate of 0.1168 g/min. The glycerol was then mixed with water by stirring. As shown in Fig. 5, this flow system made the refractive index n_c of the aqueous glycerol solution in container 2 increase linearly with time from 1.333 to 1.365 in 180 min [8]. The change Δn_c per minute was 1.809×10^{-4}.

The change in n_c caused the output signal of the TiO_2/K^+ composite OWG-based polarimetric interferometer to oscillate 24 times in 180 min (Fig. 6). The recorded intensity-time curve demonstrated that the phase-difference change, $\Delta\phi$, was a linear function of time. Therefore, under the present experimental conditions, $\Delta\phi$ was also a linear function of the refractive index n_c of the aqueous glycerol solution because of a linear dependence of n_c on time (Fig. 7). Applying this conclusion, namely, that $\Delta\phi$ depends linearly on n_c, we can see that $\Delta\phi = 2\pi$ and 1° correspond to $\Delta n_c = 1.336 \times 10^{-3}$ and 3.711×10^{-6}, respectively. For a typical MZI composed of the potassium ion-ex-

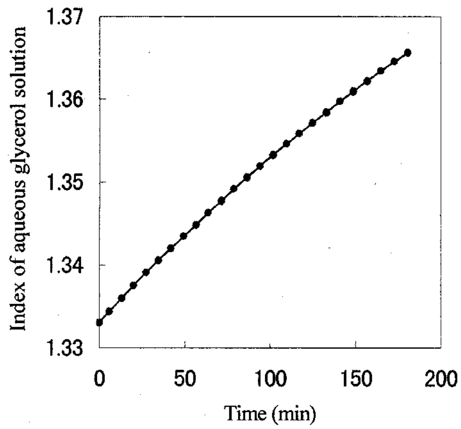

Fig. 5. Changes in the refractive index of the aqueous glycerol solution as a function of glycerol-injection time

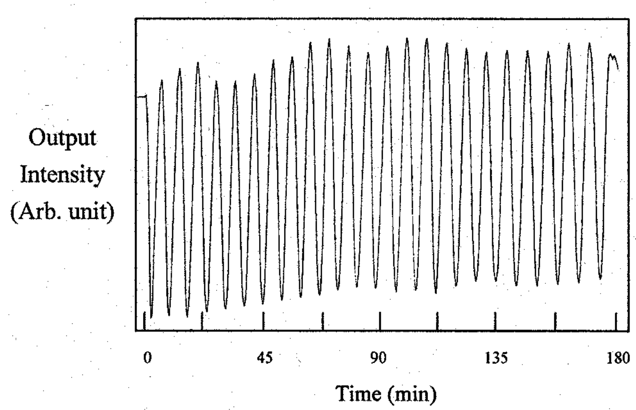

Fig. 6. Oscillation of the output intensity of the TiO_2/K^+ composite OWG-based polarimetric interferometer with the glycerol-injection time

changed channel waveguides reported in literature 9, $\Delta\phi = \pi$ corresponded to $\Delta n_c = 0.023$ in the case of a 10 mm-long active arm. Therefore the sensitivity of the TiO_2/K^+ composite OWG-based polarimetric interferometer is 68 times greater than that of a conventional MZI. When the same TiO_2/K^+ composite OWG was used as the polarimetric interferometer in an analysis of various index-unknown solutions, the indexes could be deduced from the recorded interference pattern associated with Fig. 7, which served as the standard $\Delta\phi$–n_c curve. Moreover, the results were more accurate than those calculated using guided-wave equations because some parameters used for calculation cannot be measured exactly, e.g., the refractive index and thickness of the potassium ion-exchanged layer.

In this paper, we emphasized TE_0–TM_0 mode segregation in the composite OWG because in this case the polarimetric interferometer was highly sensitive to the measurand. In fact, an upper film with a thickness below the cutoff condition of the TE_0 mode, which cannot cause TE_0–TM_0 segregation, can also introduce a difference in the evanescent interaction with the analyte between the TE_0 and TM_0 modes in the potassium ion-exchanged layer (see insert in Fig. 2). Hence, such an OWG can also be used as the polarimetric interferometer for response

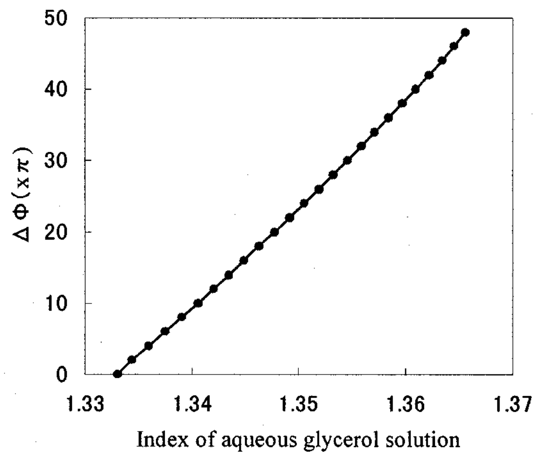

Fig. 7. The phase-difference changes $\Delta\phi$ of the TiO_2/K^+ composite OWG-based polarimetric interferometer as a function of the index n_c of the aqueous glycerol solution.

to changes in superstrate index or layer thickness. However, the sensitivity decreases in such a case.

IV. Conclusion

We have discovered a new phenomenon of TE_0–TM_0 mode segregation inside TiO_2/K^+ composite OWGs. Applying this new discovery, we designed and demonstrated a new polarimetric interferometer. The novel polarimetric interferomter is extremely inexpensive and yet is highly sensitive, and is easy to manufacture and operate. Such an OWG can be used repeatedly as a refractometer. When this type of OWG is applied to chemical and biological sensors by using the well-established surface-immobilization technique of specific recognition molecules, it fits scale production as a disposable detecting head. Like the use of single-use syringes in hospitals, the single use of chemical and biological sensors can negate poor repeatability arising from partially irreversible interaction of indicators with analytes. Composite OWG-based polarimetric interferometry is a promising new method for monitoring OWG surface changes and is superior to most OWG sensing principles in some cases.

Finally, it should be noted that by using physically sensitive materials as the upper thin film of the composite OWG, such a polarimetric interferometer could also be designed for measuring temperature, electric field strength, and pressure.

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