Broadband differential interference in a waveguide with a gradient refractive index distribution

Kazimierz Gut[*]

Silesian University of Technology, Department of Optoelectronics, 2 Krzywoustego St., 44-100 Gliwice, Poland

Received May 26, 2022; accepted September 27, 2022; published September 30, 2022

Abstract—The paper presents a planar broadband differential waveguide interferometer model with a gradient refractive index distribution. Its response to a change in the refractive index of the waveguide cover layer is presented. The analysis was performed for a wavelength range of 0.5µm–0.7µm. The orthogonal TE_0 and TM_0 modes propagating in this wavelength range are considered. The influence of the coverage refractive index change on the output characteristics of the system is shown.

Waveguide interferometers are used in many chemical and biochemical sensors [1]. The development of new detection techniques and broad access to waveguide spectrometers enabled the creation of a new group of sensors, the so-called broadband waveguide interferometers [2]. In this case, light in a particular spectral range is introduced into the interferometer. The output signal is recorded with a spectrometer. Changing the waveguide path's optical or geometric parameters changes the output signal's spectral distribution. The published papers show the operation of Mach-Zehnder [3–5], Young [6], and differential interferometers [7–8]. In this type of interferometer, the evanescent optical wave field examines the cover of the waveguide. A change in the refractive index of the waveguide cover results in a phase change of the guided mode. In gas sensors, a sensor layer may be deposited on the surface of the waveguide. Changing the optical parameters of the layer leads to a phase change of the propagated modes [9]. The research of a differential interferometer working on one selected wavelength as a chemical and biochemical sensor was carried out by Prof. Walter Łukosz [10].

Figure 1 shows the considered waveguide structure. Glass was used as a substrate. The waveguide area is the area of the glass in which the value of the refractive index has been increased by the ion exchange method. Water was taken as the cover, as is usually done in biochemical systems.

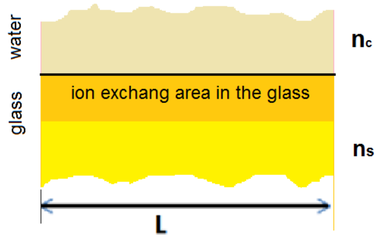

Fig.1. The considered waveguide structure: substrate (glass), waveguide layer (s), cover (water).

Based on the data provided in [11], the refractive profiles shown in Fig. 2 (typical for the Na^+/K^+ ion exchange) were adopted to determine the propagation constants.

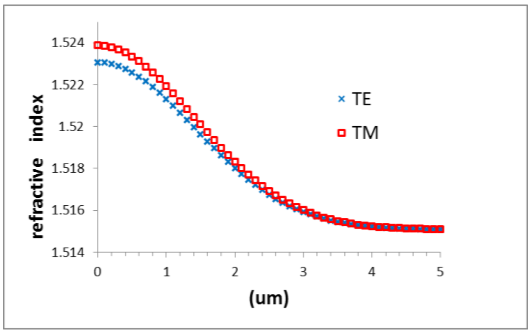

Fig. 2. Refractive index profile for TE and TM polarization in a planar waveguide.

Due to a relatively significant difference in the radii of the exchanged ions, in this case, different refractive profiles for the TE and TM polarization must be obtained. In the single-stage ion exchange process, the highest value of the refractive index is obtained on a glass surface. As the distance from the surface increases, the value of the refractive index decreases to the value of the substrate's refractive index.

The values of effective refractive indices of orthogonal modes TE and TM for different wavelengths were determined using the 2D Mode Solver module of the

---

[*] E-mail: kazimierz.gut@polsl.pl

commercial Optiwave Software. The obtained dependencies are shown in Fig. 3.

In the waveguide case, only the fundamental mode TE_0 and the TM_0 propagate in the entire range of the spectrum from 0.5µm to 0.7µm. Such a wavelength range has been chosen due to the broadband sources available. The value of the difference in the propagation constants decreases monotonically with increasing wavelength.

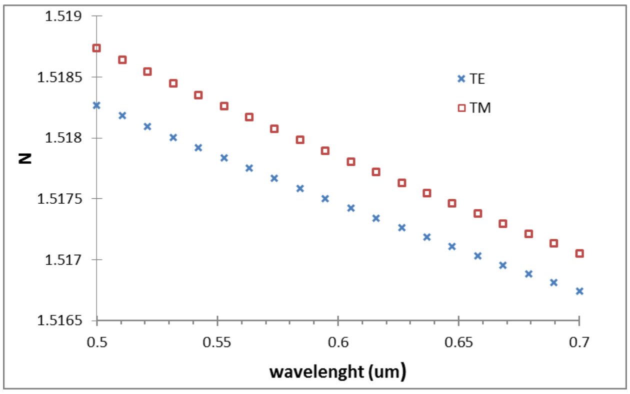

Fig. 3. Dependence of the effective refractive indexes on wavelength for TE and TM modes.

In a typical differential interferometer, light (from a source with a known spectral distribution $I_{in}(\lambda)$) injected into a waveguide cause propagation of the TE_0 and TM_0 fundamental modes. At the output of the waveguide, the polarizer brings the light from both modes to one polarization with the spectral distribution $I_{out}(\lambda)$ [7]. To describe a broadband interferometer, the propagation constants β are usually used, which describe the phase change of the modes per unit propagation path. Knowing N_{eff}, it is possible to calculate β from the formula [7]:

$$\beta(n_c, \lambda) = 2\pi N(n_c, \lambda)/\lambda, \qquad (1)$$

The intensity of light at the end of the optical path can be expressed by the formula [7]:

$$I_{out}(\lambda) = I_{in}(\lambda)\{1+\cos[\Delta\phi]\}/2, \qquad (2)$$

where Δϕ is the phase difference between the modes of the waveguide. The phases Δϕ is a function of the length of the path of propagation L, the difference of the propagation constants $[\beta_{TM0} - \beta_{TE0}]$ [8]:

$$\Delta\phi(n_c, \lambda, L) = [\beta_{TM0}(n_c, \lambda) - \beta_{TE0}(n_c, \lambda)]\, L, \qquad (3)$$

The propagation constants of orthogonal modes were calculated, and their difference assumed water as a cover. The determined dependence can be seen in Fig. 4. The dashed line in Fig. 4 shows the relationship for the refractive index greater by 0.01.

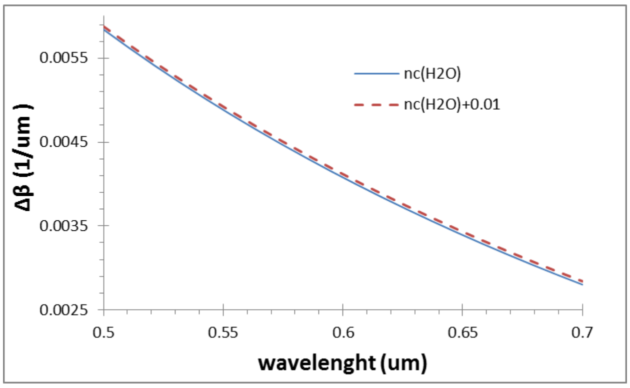

Fig. 4. Dependence of the difference of the propagation constants as a function of the wavelength.

The value of the difference in propagation constants decreases monotonically with an increasing wavelength. Such a dependence is shown by the measurement data presented in [12]. Equation (2) can be written as:

$$I_{out}(\lambda)=T(n_c, \lambda, L)\; I_{in}(\lambda), \qquad (4)$$

where T(λ, L, RH) is the factor in the equation that causes the change in the $I_{out}(\lambda)$ spectrum. $T(n_c, \lambda, L)$ is a function of propagation path length, wavelength, and refractive index of cover:

$$T(n_c, \lambda, L) = \{1+\cos[\Delta\phi(n_c, \lambda, L)]\}/2. \qquad (5)$$

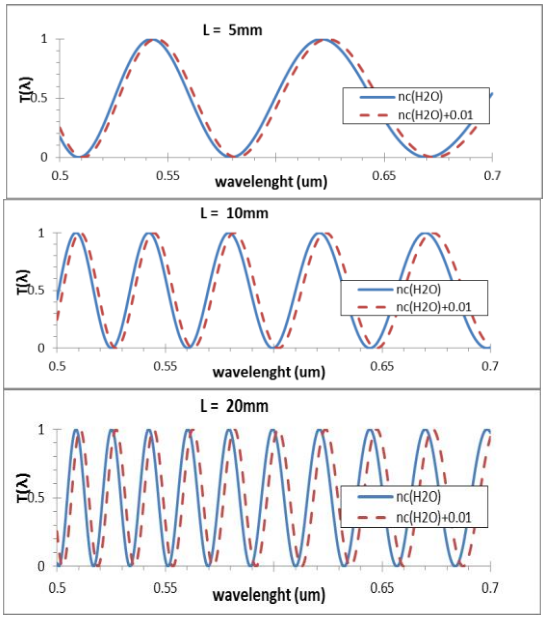

Fig. 5. $T(n_c, \lambda, L)$ for the optical path length L_1=5mm, L_2=10mm and L_3=20mm, if the waveguide cover is water (solid line); and when it increases by 0.01 refractive index of the cover (dashed line).

Figure 5 shows T (n_c, λ, L) for the optical path length L_1 = 5mm, L_2 = 10mm and L_3 = 20mm if the waveguide cover is water (solid line); and when it increases by 0.01 refractive index of the cover (dashed line).

The determined characteristics T(n_c, λ, L) have a sinusoidal shape. Increasing the length of the propagation path increases the number of extremes in the determined characteristics. The increase in the coverage refractive index causes the extremes of the determined characteristics to shift towards the waves of greater length. As shown in the publication [8], the shifts of the extremes δλ resulting from the change of the cover refractive index δn_c, can be expressed by the formula:

$$\delta\lambda \approx -\frac{\frac{\partial(\Delta\beta)}{\partial n_c}}{\frac{\partial(\Delta\beta)}{\partial\lambda}}\,\delta n_c, \tag{6}$$

where: $\frac{\partial(\Delta\beta)}{\partial n_c}$ is the partial derivative of the function $\Delta\beta(\lambda,n_c)$ with respect to the cover refractive index, $\frac{\partial(\Delta\beta)}{\partial\lambda}$ is the partial derivative of the function $\Delta\beta(\lambda,n_c)$ with respect to the wavelength, for the analyzed waveguide structure shown in Figure 1. It is worth noting that the shift of the extremes does not depend on the propagation path length. The dependence of extremes shift and wavelength is shown in Fig. 6 (for the refractive index change of the coverage amounting to 0.01).

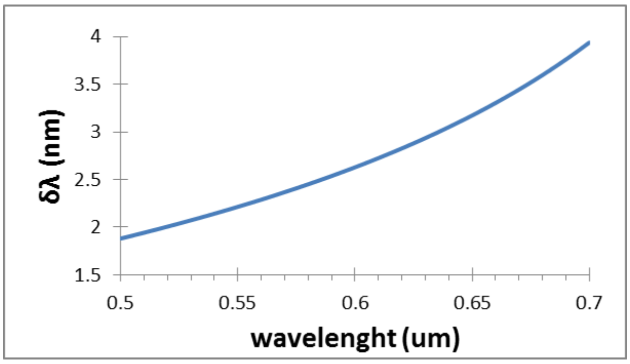

Fig. 6. Dependence of extremes shift as a function of wavelength (for the refractive index change of the cover amounting to 0.01).

Ion exchange is a relatively cheap and cost-effective technology [13–14]. Usually used when there is a need to make a prototype circuit. The presented work shows how the cover refractive index changes the spectrum of the output signal in a broadband differential interferometer based on a waveguide obtained with the ion exchange technique. In this case, with the increase of the refractive index of the coverage, the difference in the propagation constants of the orthogonal modes increases.

It is also worth noting that the spectrum change takes place over the entire considered wavelength range, enabling efficient use of commercial fiber optic spectrometers.

References

[1] P. Kozma, F. Kehl, E. Ehrentreich-Forster, C. Stamm, F.F. Bier, Biosens. Bioelectron. **58**, 287 (2014).

[2] M. Kitsara, K. Misiakos, I. Raptis, E. Makarona, Opt. Expr. **18**, 8193 (2010), https://opg.optica.org/DirectPDFAccess/24C0798C-C8A7-4E1B-B00B4DDD45B132F2_197034/oe-18-8-8193.pdf?da=1&id=197034&seq=0&mobile=no

[3] K. Misiakos, I. Raptis, A. Salapatas, E. Makarona, A. Bostials *et al.*, Opt. Expr. **22**, 8856 (2014), https://opg.optica.org/DirectPDFAccess/45B60384-DFE1-4704-9DEEBC82D6BE62A5_282812/oe-22-8-8856.pdf?da=1&id=282812&seq=0&mobile=no

[4] K. Misiakos, I. Raptis, E. Makarona, A. Botsialas, A. Salapatas *et al.*, Opt. Expr. **22**, 26803 (2014), https://opg.optica.org/DirectPDFAccess/767E0999-718E-4A4E-A88F7582FB5A88E5_303282/oe-22-22-26803.pdf?da=1&id=303282&seq=0&mobile=no

[5] K. Misiakos, E. Makarona, M. Hoekman, R. Fyrogenis, K. Tukkiniemi et al., ACS Photonics **6**, 1694 (2019).

[6] E. Makarona, A. Salapatas, I. Raptis, P. Petrou, S. Kakabakos, *et al.*, J. Opt. Soc. Am. B **34**, 1691 (2017).

[7] K. Gut, Opt. Expr. **25**, 3111 (2017). https://opg.optica.org/oe/fulltext.cfm?uri=oe-25-25-31111&id=377395

[8] K. Gut, Nanomaterials **9**, 729 (2019), https://www.mdpi.com/2079-4991/9/5/729

[9] T. Pustelny, J. Ignac-Nowacka, Z. Opilski, Opt. Appl. **34**, 563 (2004). https://opticaapplicata.pwr.edu.pl/article.php?id=2004400563

[10] W. Lukosz, Sensor Actuat. B-Chem. **29**, 37 (1995).

[11] Z. Qi, S. Xia, N. Matsuda, Opt. Expr. **16**, 2245 (2008), https://opg.optica.org/oe/fulltext.cfm?uri=oe-16-3-2245&id=152207

[12] K. Gut, A. Zakrzewski, T. Pustelny, Acta Phys. Pol. **118,** 1140 (2010), http://przyrbwn.icm.edu.pl/APP/PDF/118/a118z6p14.pdf

[13] J.E. Broquin, S. Honkanen, Appl. Sciences, **11**, 4472 (2021), https://www.mdpi.com/2076-3417/11/10/4472

[14] G.C. Righini and J. Linare, Appl. Sciences, **11**, 5222 (2021), https://www.mdpi.com/2076-3417/11/11/5222/htm