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Spectropolarimetric analyses of optical single mode SU8 waveguide layers

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Abstract. The paper presents the principle of the operation of a spectropolarimetric interferometer. In a planar waveguide orthogonal modes of the TE and TM types can be excited for the entire visible light. During the propagation the difference of the phases between the modes was determined, which is the function of the length of the path of propagation, the difference of the effective refractive index ($\mathrm{N_{TM}}$-$\mathrm{N_{TE}}$) and the wavelength. At the output of this system the spectral distribution of intensity was recorded, the shape of which depends on the value of the refractive index of the cover of the waveguides.

Key words: interferometry, SU8 optical waveguides, optical sensors.

1. Introduction

Thanks to researches and the development of integrated optics devices for optical applications in the telecommunications, relatively cheap sources and detectors of optical radiation that can be used in the design of planar optical sensors [1, 2]. These sensors are immune to electromagnetic interferences, including the danger of electric shock and electrically initiated explosion. A huge variety of optical methods allows to the detect parameters that under the influence of external factors change their properties. Optical measuring methods are characterized by a high sensitivity and a wide range in chemical gas sensors making it possible to detect the ppb level (one molecule detected gas per billion molecules of atmosphere). Moreover, the use of optical fibers allows for easy entry of light into the system and its output, allowing remote detections and manufacturing networks of sensory structures [3]. Planar systems allow the execution of a sensor array on a single structure. Although some optical sensors have been used in niche markets to measure various physical parameters (e.g. the measurement of the electric field at power stations [4, 5], monitoring the artificial heart [6]), their highest potential (both physically and economically) permits to measure very low concentrations of biochemical and chemical components [7]. Almost always the reading system works on the following principle: a change of the measured parameter is converted to a change of the properties of the optical beam in the measurement system, leading to changes in the intensity of light recorded by the detector. One of the commonly used sensor systems is the differential interferometer, based on planar waveguides [8–11].

The increasing availability of fiber optic spectrometers and broadband light sources with a high power allows to enter the whole range of the visible spectrum to the planar waveguides [12]. In the analyzed system propagates a mode for wavelengths from 450 nm to 600 nm. This type of arrangement is shown in [12–14] and called “frequency-resolved”, “broadband” or “wavelength interrogation” Mach-Zehnder interferometer.

This paper presents the idea of a spectropolarimetric differential interferometer in which the recorded signal indicates the spectral distribution recorded at the output of the structure. Any change in the condition of propagation results in the case in a change of the recorded spectral distribution.

2. Differential interference in planar waveguides

Modes in planar optical waveguides may be either of the type TE_m (Transverse Electric) or TM_m (Transverse Magnetic) where $m = 0, 1, 2...$ is the number of the mode order. In sensor applications, an effective refractive index N is the most important physical quantity that describes the propagation modes. The modes propagate in an optical waveguide with a phase velocity $v_f = c/N$, where c is the velocity of light in vacuum. The value of N is dependent on the polarization (TE or TM), the number of the mode m, the wavelength λ, the refractive index of the waveguide layer and the refractive index cover n_c. The field of the mode penetrates as an evanescent wave a short distance Δz_c of the cover waveguide. The evanescent wave decreases exponentially in the cover according to the function $\exp\left(-z/\Delta z_c\right)$, where z is the distance from the surface of the waveguide layer and the parameter Δz_c is called penetration depth [11]

$$\Delta z_c = (\lambda/2\pi)\left[N^2 - n_c\right]^{-1/2}. \tag{1}$$

The effect of the properties of the cover on the propagation of the modes is most often a phenomena on utilized in planar waveguide sensors. The evanescent filed “feels” the changes in the distribution of the refractive index near the surface of the structure. This involves a change of the effective refractive index of the modes. These changes may be due to two different effects, viz.:

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1. the formation of an additional sensor layer, adsorbing the molecules or connected with them, the molecules being transported by convection or diffusion to the surface of the waveguide,
2. change Δn_c of the refractive index of the cover n_c of the waveguide (usually a liquid).

Only in the case of microporous waveguides there may occur a third effect, which is based on the adsorption and desorption of molecules in the pores of the layer by changing the refractive index of the waveguide layer, and thus also the effective indices of the modes. All effects can occur at the same time causing a change of effective refractive index.

The effect (1) may be applied for the purpose of monitoring during the adsorption of the molecules on the surface of the waveguide. The second effect may serve as the basis of the operation of the refractometers. Effects (1) and (2) can be the basis of the action of planar optical chemical and biochemical sensors. (2) can be used in humidity sensors, gas sensors and sensing chemical affinity. The sensor layer deposited on the surface can change all its properties (thickness, the refracting index) affected by the selected chemical parameters of the environment, resulting in a change of the constant of propagation of the applied modes. In the case of an interference of the modes TE_0 and TM_0 and the same optical power density I_0 is transmitted in both modes, (if the plane of polarization of the output polarizer is set at an angle to the surface of the optical waveguide 45°) the signal recorded by the detector $I(t)$ can be expressed by the formula [11]

$$I(\lambda,t) = I_o\{1 + \cos[\Delta\phi(\lambda,t)]\}, \tag{2}$$

where $\Delta\phi(\lambda,t)$ is the phase difference between the modes at the output of waveguide.

In the case of interference of modes of the same polarization TE_0 and TE_1 (TM_0 TM_1)), the phase shift between the modes changes the intensity of the distribution in a plane perpendicular to the direction of the propagation of light. Recording intensity of light in any part in the front of the waveguide, we can obtain the signal of interference [15].

Fiber optic spectrometers and broadband light sources with a high power which allows to enter the whole range of the visible spectrum to the planar waveguides are more or and more available [16].

We can choose the thickness which allows at a given index of refraction of the waveguide layers to propagate only fundamental modes of type TE and TM in whole range of spectrum.

In order to satisfy the conditions for coherence of the light beam before entering into the structure a polarizer must be placed at an angle of 45° to the perpendicular direction of the waveguide surface.

In the course of propagation the difference of the phases between the modes $\Delta\phi$ is attained, which is a function of the length of the path of propagation L, the difference of the effective refractive index (N_{TM}-N_{TE}) and the wavelength.

$$\Delta\phi(\lambda) = \frac{2\pi}{\lambda} L(N(\lambda)_{\mathrm{TM}} - N(\lambda)_{\mathrm{TE}}). \tag{3}$$

The second polarizer placed before the spectrometer at the same angle (45°), provides light from both orthogonal modes to one plane of polarization, permitting the recording of the signal of interference (Fig. 1).

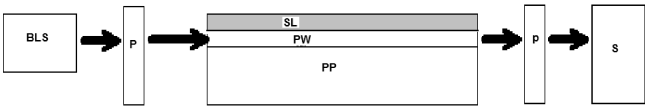

Fig. 1. Diagram of a spectropolarimetric interferometer (BLS – broadband light source, PW – planar waveguide, PP – substrate plate, P – polarizer, S – spectrometer, SL – cover)

In the numerical analysis a three-layer system has been used with the following: substrate (SiO_2), the waveguide layer (SU8), cover (water) (Fig. 2).

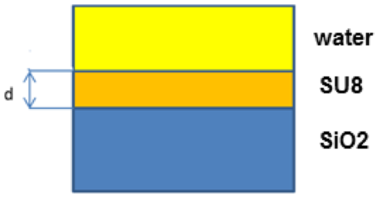

Fig. 2. Analyzed planar three-layer system

The analysis takes into account the dispersion characteristics of the substrate and the layer of SU 8 (Fig. 3), which was determined by ellipsometer SE850 SENTECH. The paper also includes dispersion coating (water).

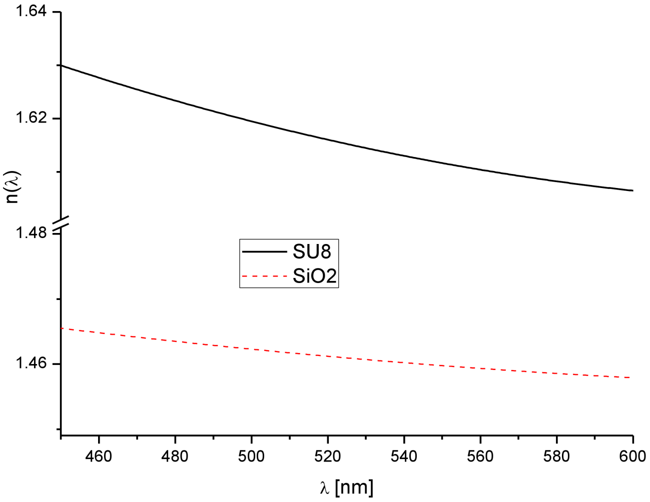

Fig. 3. Spectral characteristics of the refractive indices

Within the range of spectral refractive indices decrease monotonically depressed with the increasing length of the wave.

In order to get in the structure merely propagations of the fundamental modes TE and TM, the effective refractive indices of the modes were determined as a function of the thickness d of the waveguide layer concerning the shortest (450 nm) and the longest (600 nm) wave length (Fig. 4).

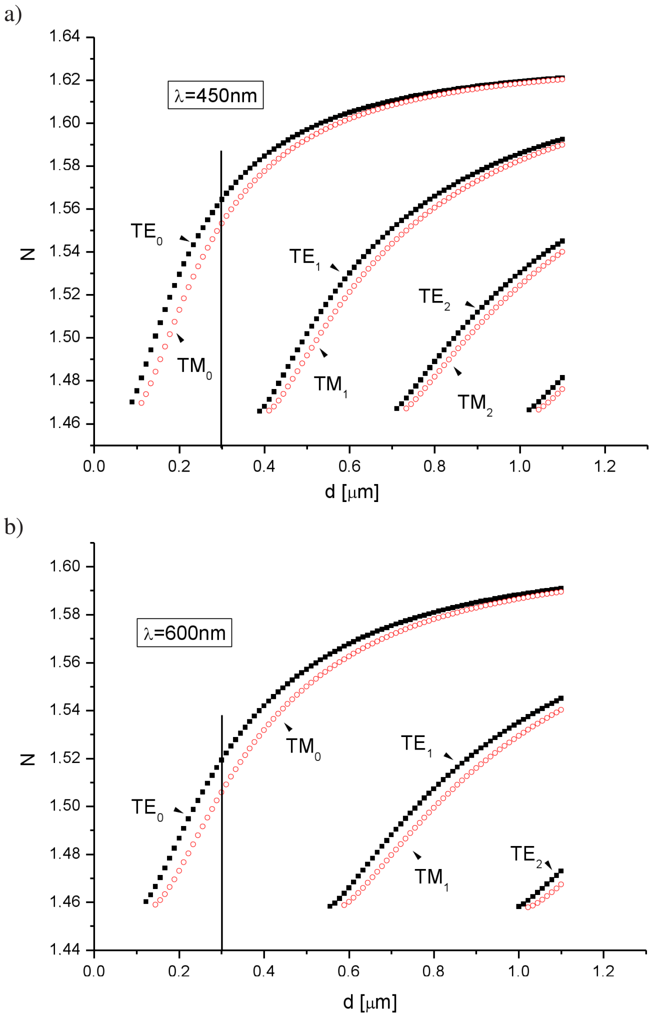

Fig. 4. Effective refractive indices as a function of the thickness d of the layer SU8, a) at a wavelength of 450 nm, b) at a wavelength of 600 nm

For the waveguide layer with a thickness $d = 0.3$ μm the propagation is only possible in the case of fundamental modes TE_0 and TM_0 (high order modes for the waveguide layer thickness cannot propagate) at a wavelength of the whole considered section.

Figure 5 presents the values of effective refractive indices of the fundamental modes TE_0 and TM_0 in the considered range of wavelengths with a thickness of the waveguide layer amounting to 0.3 μm.

In order to determine the phase change after having passed the length L it is important to know the effective refractive indices of the fundamental modes. The determined dependence is to be seen in Fig. 6. The value of the difference effective indices of refraction fundamental modes increases with the growth of the wavelength.

According to the relation (3) the phase shift $\Delta\phi$ between the orthogonal fundamental modes is directly proportional to the product of the difference of the effective indices and the length of the propagation path and inversely proportional to the wavelength. The differences of the phase between the modes $\Delta\phi(\lambda)$ after passing the length L have been determined concerning the whole spectral range (from 450 nm to 600 nm) basing on relation (3).

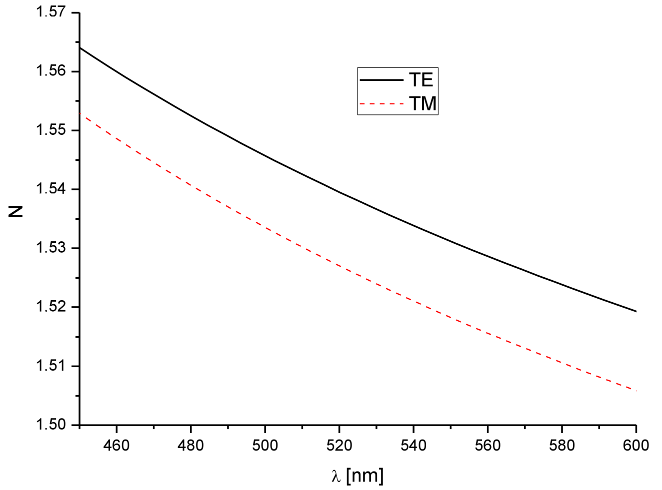

Fig. 5. Dependence of the effective refractive indices as a function of the wavelengths (SU8 thickness of 0.3 μm)

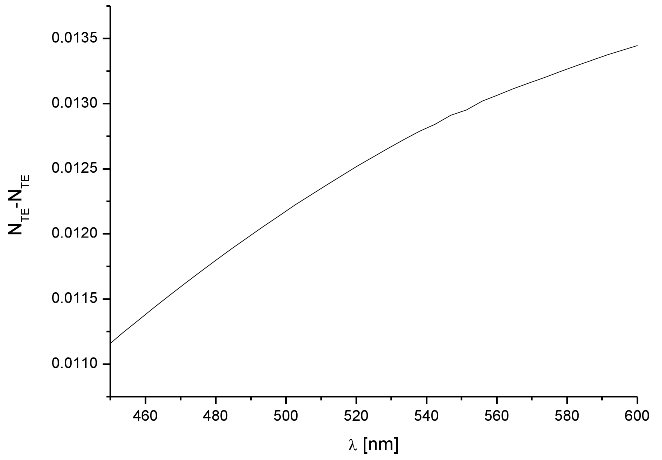

Fig. 6. Dependence of the difference of the effective refractive indices as a function of the wavelength

Assuming the same intensity of light $I_0(\lambda)$ in the orthogonal modes, a normalized light intensity $I_n\ (\lambda)$ could be defined as:

$$I_n(\lambda) = \frac{I_o(\lambda)\{1 + \cos[\Delta\phi(\lambda)]\}}{I_o(\lambda)}. \tag{4}$$

Figure 7 presents the normalized light intensity distribution concerning the length of the propagation path 1 mm, 2 mm and 4 mm.

Figure 8 presents the normalized light intensity distribution concerning the refractive indices of the cover $n_C = n_{\mathrm{H2O}}$ and $n_{Ci} = n_{\mathrm{H2O}} + i \times 0.001$ $(i = 1, 2, 3)$ for the length of the propagation path $L = 1$ mm.

A change of the refractive index of the cover of the waveguide in a spectropolarimetric interferometer results in a change of the distribution of power in the spectrum transmitted by the considered system.

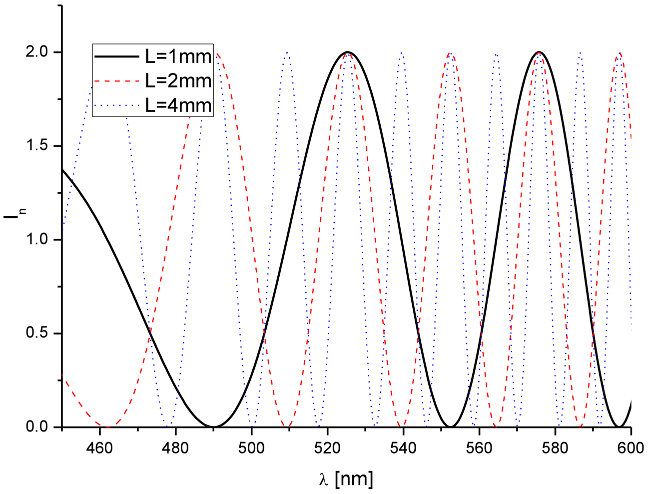

Fig. 7. Normalized light intensity distribution I_n (λ) the length of the propagation path 1 mm, 2 mm and 4 mm

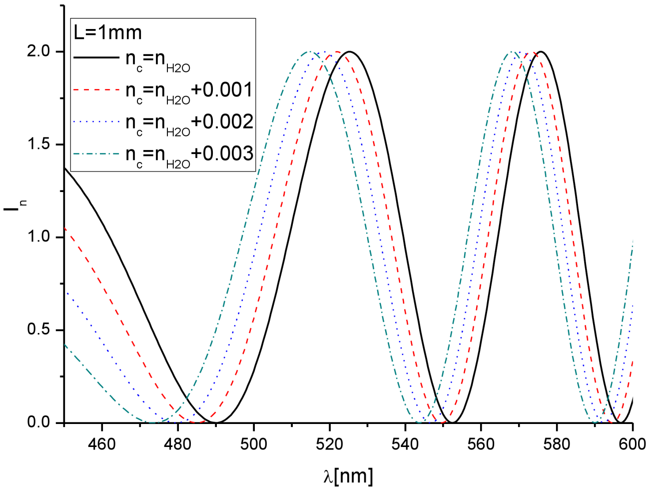

Fig. 8. Normalized light intensity distribution I_n (λ) for different indices of refraction of the coating layer

3. Conclusions

Due to a monotonic change, the measured quantity in the differential interferometer we get a sinusoidal signal. The same variation in measurements results in different change of the signal depending on the initial value. In particular situations changes in the measurement do not change the value of the light intensity at the output of the system.

In the spectropolarimetric interferometer the information about the value of the refractive index of the cover is connected with the spectral distribution transmitted by the system. A change of this parameter results in a monotonic shift of extreme values concerning the spectral distribution of light recorded by the spectrometer.

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