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Application of planar monomode waveguides to determine parameters of thin active layers used in waveguide sensors

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The presence of a thin cover layer on the planar waveguide influences its propagation characteristics. This effect has been taken advantage of in the *m*-line spectroscopy of the four-layer structure for evaluation of a thickness and refractive index of a thin organic cover layer used as a sensing medium for fiber optic and/or planar sensors. Because due to the small thickness the organic layers do not guide light by themselves, the generalised *m*-line spectroscopy is a simple and convenient method alternative to conventional measurement of thin layers. The effect of the cover layer is pronounced for low-mode waveguides, especially for single-mode waveguides. But for the latter one can neither solve the dispersion equation nor evaluate the thickness and the refractive index knowing merely a single coupling angle of a structure. An additional measurement of the coupling angle for a beam of different wavelength yields the second equation and assuming that the difference between the waveguide dispersion and substrate dispersion is negligible, results in evaluation of the thickness and refractive index of the layer.

1. Introduction

In order to control the parameters of thin organic layers (*i.e.*, refractive index and thickness) one can simply and easily utilise a generalised method of *m*-line spectroscopy. This method can be employed to investigate active layers (applied for sensors) in which some reagents are immobilised as well as for investigation of waveguide protective layers.

The *m*-line spectroscopy is a well-known measuring method applied when we have to deal with a layer guiding the light, that is, a waveguide [1]. Organic layers covering the waveguide can remarkably change coupling angles of the light into the waveguide.

The aim of this paper is to show that we can evaluate in a simple way the parameters of a layer which has a sub-waveguide thickness but when deposited on a waveguide it contributes to light-guiding. If we carry out measurements at different wavelengths we can also evaluate parameters of single-mode wave-guides.

2. Measuring method

2.1 Generalised method for determination of structure parameters

A three-layer structure represented by a waveguide on a substrate and with an air cover is characterised by refractive indexes n_g, n_s and n_t, respectively, as well as by the waveguide thickness W

A dispersion equation for such a structure for TE mode can be expressed in the following way [1]:

$$k\sqrt{(n_g^2-N_{\mathrm{eff},m}^2)}\,W = \tan^{-1}\frac{\sqrt{(N_{\mathrm{eff},m}^2-n_s^2)}}{\sqrt{(n_g^2-N_{\mathrm{eff},m}^2)}}+\tan^{-1}\frac{\sqrt{(N_{\mathrm{eff},m}^2-n_t^2)}}{\sqrt{(n_g^2-N_{\mathrm{eff},m}^2)}}+m\pi \tag{1}$$

where: m – mode number ($=0, 1, 2, 3,\ldots$), $N_{\mathrm{eff},m}$ – effective refractive index for a three-layer structure for the given mode m.

A numerical solution of a set of two, at least, equations will yield a refractive index and waveguide thickness.

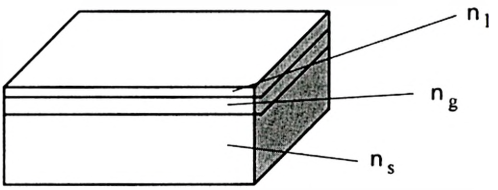

Fig. 1. Four-layer structure.

For four-layer structure (Fig. 1) the dispersion equation takes a more complicated form [2]:

$$kW\sqrt{(n_g^2-\tilde{N}_{\mathrm{eff},m}^2)} = \tan^{-1}\left(\frac{A_1}{B_1}\right)+\tan^{-1}\left(\frac{C_1+D_1}{E_1+F_1}\right)+m\pi \tag{2}$$

where: $A_1 = \sqrt{(\tilde{N}_{\mathrm{eff},m}^2-n_s^2)}$,

$B_1 = \sqrt{(n_g^2-\tilde{N}_{\mathrm{eff},m}^2)}$,

$C_1 = \sqrt{(\tilde{N}_{\mathrm{eff},m}^2-n_l^2)}\,\sqrt{(\tilde{N}_{\mathrm{eff},m}^2-n_t^2)}\,\cosh\left(kt\sqrt{(\tilde{N}_{\mathrm{eff},m}^2-n_l^2)}\right)$,

$D_1 = (\tilde{N}_{\mathrm{eff},m}^2-n_l^2)\sinh\left(kt\sqrt{(\tilde{N}_{\mathrm{eff},m}^2-n_l^2)}\right)$,

$E_1 = \sqrt{(n_g^2-\tilde{N}_{\mathrm{eff},m}^2)}\,\sqrt{(\tilde{N}_{\mathrm{eff},m}^2-n_l^2)}\cosh\left(kt\sqrt{\tilde{N}_{\mathrm{eff},m}^2-n_l^2}\right)$,

$F_1 = (\tilde{N}_{\mathrm{eff},m}^2-n_t^2)\sinh\left(kt\sqrt{(\tilde{N}_{\mathrm{eff},m}^2-n_l^2)}\right)$

(n_l – refractive index of the layer covering the waveguide, n_g, n_s and n_t – as above, t – thickness of the layer, $k=2\pi/\lambda$ – wave vector, $\tilde{N}_{\mathrm{eff},m}(\neq N_{\mathrm{eff},m})$ – effective refractive index for the given m of the four-layer structure).

If n_l is larger than n_g Equation (2) takes a different form

$$kW\sqrt{(n_g^2-\tilde{N}_{\mathrm{eff},m}^2)} = \tan^{-1}\left(\frac{A_2}{B_2}\right)+\tan^{-1}\left(\frac{C_2-D_2}{E_2+F_2}\right)+m\pi \tag{3}$$

where: $A_2 = \sqrt{(\tilde{N}_{\mathrm{eff},m}^2-n_s^2)}$,

$B_2 = \sqrt{(n_g^2-\tilde{N}_{\mathrm{eff},m}^2)}$,

$C_2 = \sqrt{(n_l^2-\tilde{N}_{\mathrm{eff},m}^2)}\sqrt{(\tilde{N}_{\mathrm{eff},m}^2-n_t^2)}\cos(kt\sqrt{(n_l^2-\tilde{N}_{\mathrm{eff},m}^2)})$,

$D_2 = (n_l^2-\tilde{N}_{\mathrm{eff},m}^2)\sin(kt\sqrt{(n_l^2-\tilde{N}_{\mathrm{eff},m}^2)})$,

$E_2 = \sqrt{(n_g^2-\tilde{N}_{\mathrm{eff},m}^2)}\sqrt{(n_l^2-\tilde{N}_{\mathrm{eff},m}^2)}\cos(kt\sqrt{n_l^2-\tilde{N}_{\mathrm{eff},m}^2})$,

$F_2 = \sqrt{n_g^2-\tilde{N}_{\mathrm{eff},m}^2}\sqrt{\tilde{N}_{\mathrm{eff},m}^2-n_t^2}\sin(kt\sqrt{n_l^2-\tilde{N}_{\mathrm{eff},m}^2})$.

Using the value of waveguide parameters (n_g and W calculated for a three-layer structure, that is, before deposition of a thin layer) we can determine parameters (n_l and t) of the layer deposited on the waveguide.

2.2 Determination of parameters of thin layers using laser light with different wavelengths

The dispersion Equation (2) or (3) for different $k_1 = 2\pi/\lambda_1$ and $k_2 = 2\pi/\lambda_2$ splits into two equations. At different wavelengths the change of light propagation results from the change of effective refractive index in the waveguide.

For transparent medium such as a glass substrate its dispersion is satisfactorily expressed by Cauchy formula [3]:

$$n = A+\frac{B}{\lambda^2}+\frac{C}{\lambda^4} \tag{4}$$

where the constants A, B, C equal:

$A = 1.4755$,

$B = 0.0136\times10^{-12}\ \mathrm{m}^2$,

$C = -0.0008\times10^{-24}\ \mathrm{m}^4$.

In the case where the layer is deposited on a mono-modal waveguide the changes of effective refractive index are larger depending on the thickness t of the deposited layer, as plotted in Fig. 2 [5].

Therefore, the above method enables us to determine parameters of a thin layer in the case where the waveguide is mono-modal. The method adds to the possibilities of generalised spectroscopy of m-line because four-layer structures are only once under study, which means that it is not necessary to carry-out measurements before and after deposition of a thin layer on the waveguide. The measurements carried out before deposition of a thin layer can be used for self-consistence of the method.

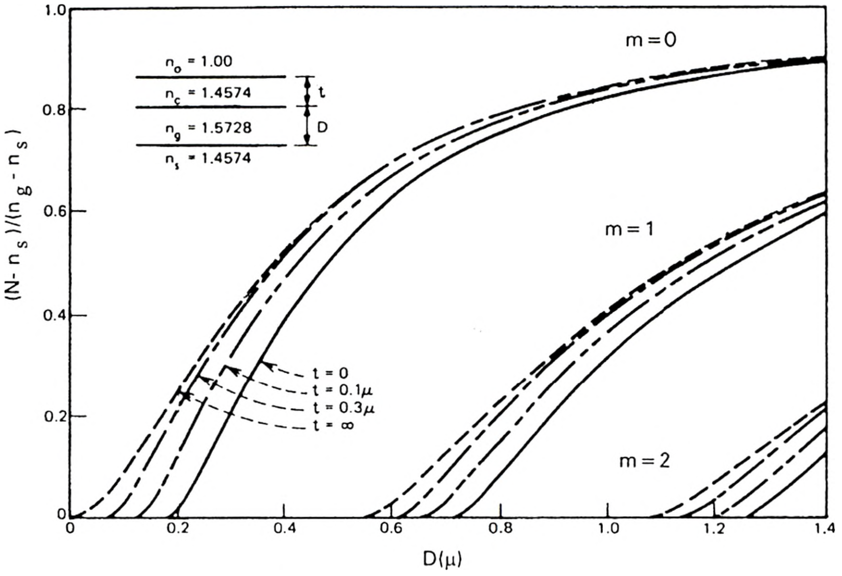

Fig. 2. Dependence of the effective index N on waveguide thickness D and covered layer thickness t [5].

3. Experimental

3.1 Preparation of samples

Planar waveguides used in the measurements were prepared by the glass ion-exchange method. Single mode waveguides were covered by:

a) multilayers from UV-cross-linked 11-trichlorosilyloundecene,

b) spin-coating polyimide films from N-methylopirolidone solutions.

Multilayers (a) were prepared by casting 11-trichlorosilyloundecene tolulol solutions and then they were cross-linked by the UV-radiation. Thin polyimide films (b) were spin-coated onto the waveguides prior to being modified with the coupling agent 3-aminopropyltrietoxysilane. The spin-coating speed was varied from 2000 to 4000 revolutions per second.

3.2 Measuring set-up

A scheme for coupling angle measurements is depicted in Fig. 3. For measurements there were used two lasers emitting at the wavelengths: $\lambda_1 = 632.8$ nm and $\lambda_2 = 543.5$ nm.

The light was coupled into the waveguide by a glass prism of the refractive index $n_p = 1.7499$. The measurements were carried out for TE modes. In the close proximity of the waveguide the light wave suffers some losses in total reflection from the prism base and excites only the mode propagation in the waveguide for discrete coupling angles α_λ.

The use of symmetrical prism causes a reverse effect, that is, decoupling of the light, but this time in the form of bright lines observed on the screen. By measuring

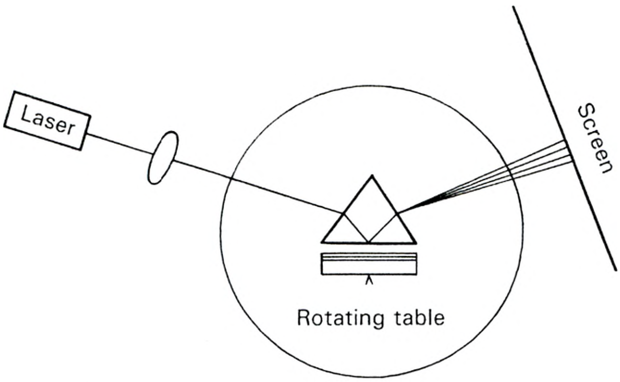

Fig. 3. Scheme of coupling angle measurements.

the coupling angles, *i.e.*, angles of coupling and propagation of light along the waveguide, we can determine – based on a simple geometric dependence – the effective refractive indexes for the two wavelengths

$$N_{\mathrm{eff},\lambda} = \sin\alpha_\lambda \cos\varepsilon + \sqrt{(n_p^2 - \sin^2\alpha_\lambda)} \sin\varepsilon. \tag{5}$$

From the measurements of the four-layer structure for the two wavelengths as well as taking into account the substrate dispersion one can determine the parameters of a thin layer.

4. Results

In Table 1, the results of coupling angle measurements are presented for the waveguide before and after deposition of a thin layer and calculated effective refractive indexes ($\lambda = 632.8$nm) showing a remarkable change in the coupling angle and N_{eff}. Samples marked by digits and small letters are waveguides with deposited layers of 11-trichlorosilyloundecene, while samples marked by capital letters are waveguides with deposited polyimide layers of different thicknesses [6].

Table 1. Results of coupling angle measurements before and after deposition of a thin layer and calculated effective refractive indexes and thicknesses.

Sample No.	Coupling angle α_m (waveguide)	N_{eff} (waveguide)	Coupling angle α_m (waveguide with thin film)	$N_{\mathrm{eff},m}$ (waveguide with thin film)	Thickness [μm]
4	27°05′	1.5157	28°35′	1.5285	3.03
2c	27°10′	1.5174	28°50′	1.5305	3.12
5d	26°25′	1.5113	28°00′	1.5240	3.47
K	26°25′	1.5113	26°41′	1.5134	2.34
N	26°50′	1.5146	27°44′	1.5218	2.45

Changes in the coupling angle after deposition of a layer are by one order larger as compared with measuring accuracy of 0.5′.

Table 2. Results of coupling angle measurements and calculated effective refractive indexes for two wavelengths of light in the four-layer structures.

Sample No.	Angle of coupling α_λ		N_{eff}		Thickness [μm]
	$\lambda_1 = 632.8$ nm	$\lambda_2 = 543.5$ nm	$\lambda_1 = 632.8$ nm	$\lambda_2 = 543.5$ nm	
5d	28°00′	28°11′	1.5240	1.5254	3.47
2c	28°50′	29°01′	1.5305	1.5318	3.12

Table 2 shows examples of coupling angle measurements and calculated effective refractive indexes for the two wavelengths in the four-layer structure (mono-modal waveguides with deposited thin layer).

Therefore, we can also notice the change of coupling angles and effective refractive indexes ($\alpha_{\lambda=543.5\ \mathrm{nm}} = 26°28'$ for sample 5d before deposition of the thin layer).

For verification purposes, the results of calculations of layer thicknesses, assuming $n_t = 1.0002$, $n_l = 1.5450$, $n_g = 1.5400$, $n_s = 1.5045$, and the same substrate and waveguide dispersion, are shown in the last columns of Tabs. 1 and 2; and these are satisfactory. Evaluation of the thickness with the method developed has an advantage as compared to ellipsometry. The generalised method of *m*-line spectroscopy is insensitive to the surface roughness.

5. Conclusions

A change in the coupling angles after deposition of a thin film on a waveguide is by one order of magnitude bigger compared to measuring accuracy. Therefore, the advantage of the above method lies in its great sensitivity to changes in parameters of an active thin film. The generalised method extends the measuring ability of *m*-line spectroscopy to films that do not meet the waveguide criteria (refractive index and thickness).

For measurements the presented method utilises light sources of different wavelengths. The method simplifies evaluation of the parameters of thin organic films. With the two-wavelength procedure single-mode waveguides can be studied with relatively high sensitivity. The initial study seems to be very promising and confirming the expectations. The method can be easily applied to control of thin films prepared for fiber sensors.

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