Polymer waveguides obtained by deposition from solution

Codruta Mirica[1], Ion N. Mihailescu[1], V. Vasiliu[1], Stefan Levai[2]

[1] Institute of Atomic Physics, Laser Department
Bucharest, P.O.Box MG-54, R-76900 Romania

[2] Bucharest University, Physics Faculty,
Bucharest, P.O.Box MG-11, R-76900 Romania

1. Introduction

Integrated optical devices are essential for an economical realization of optical communication systems. The common feature of all these devices is that the optical wave propagates along a waveguide. Therefore waveguides do not only interconnect different components, but they are themselves the main part of each optical component.

As their importance is so great, they are equally studied our days as well as they were 20 years ago, permanently trying to improve their quality and to diminish their costs.

Accordingly to the theory of light propagation, waveguiding depends on the difference in the refractive index between the waveguiding region and the surrounding media [1÷3].

A great number of techniques can be used for obtaining the required index difference. Each method has particular advantages and disadvantages, so that none of them could be said to be clearly superior. The choice of the method depends on the required application and on some general requests that must be fulfilled by the optical waveguide [1,4].

Such general requests are tied of:

- the waveguide must be transparent for propagating radiation;
- the thickness of the waveguide must be comparable with that of the radiation wavelength;
- the refractive index of the waveguide must be greater than those of the surrounding media;
- the waveguide must be long enough for making possible the coupling with the other components of the optical system.

The method is chosen by taking into account all these requests and, additionally, the type of the optical waveguide that must be realized (symmetric or asymmetric, simple or multilayer, etc.) and the maximum acceptable value of the propagation loss.

The waveguide will work in an integrated optical circuit if some properly chosen techniques and devices for coupling the radiation into the waveguide are used. The coupling method is chosen depending on the radiation to be coupled and on the waveguides type.

2. Experimental results and discussions

The purpose of this experiment was to obtain an optical planar waveguide and to obtain the input/output coupling of a laser beam to this waveguide, using prism couplers.

The scheme for coupling setup is presented in Fig. 1. The components of such a setup are: the substrate on which the waveguide should be obtained (denoted by *1* in Fig. 1), the thin guiding layer (denoted by *2*) and the coupling prisms (denoted by *3*).

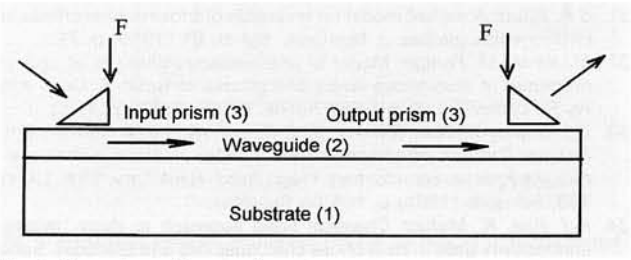

Fig. 1. The scheme for coupling setup

2.1. Substrates

The substrates were plates made of ordinary glass. Their refractive index was measured, with a precision of 10^{-5}, using a Pulfrich refractometer. The results taken at λ=546 nm and λ=656 nm are given in Table 1.

2.2. Prisms

The prisms were of two types: made of TF102 and TK119 glass. They were characterized using Pulfrich refractometer for measurement of refractive index and the goniometric method for measurement of angles and refractive index. The prisms were right-angle and the obtained refractive indices are given in Table 2.

Using prism couplers for optical planar waveguides is very convenient because then the efficiency can increase up to 80% [1]. If more than one modes propagate within the guide, the light is coupled in/out at specific angles corresponding to each mode. The efficiency can be determined independently for each mode as the following ratio:

$$\eta_{C(m)} = \frac{\text{power coupled into (out of) the m}^{\text{th}}\text{ order mode}}{\textit{total}\text{ power in optical beam prior to coupling}} \quad (1)$$

Because of this characteristic, the prism coupler can be used as an analytical tool to determine the relative power in each waveguide mode. The prism can also be moved along the waveguide length to determine losses [6,7].

The coupling occurs when the phase velocities of waves in the direction of propagation z are the same both in the waveguide and in the beam. For obtaining a phase-match condition it is necessary that the refractive index n_p of the prism to be greater than that of the surrounding (upper) medium of the waveguide n_1 (see Fig. 2).

Table 1. Substrates refractive indices

Substrate	λ=546 nm		λ=656 nm	
	angle	n	angle	n
plate 1	28°32.03′	1.51142	28°27.82′	1.511083
plate 2	29°33.26′	1.50010	28°44.86′	1.49610
plate 3	28°22.63′	1.51066	28°02.54′	1.50905

Table 2. Prisms refractive indices

Prism	λ=5461 Å		λ=6563 Å	
	angle	n	angle	n
TK119	81°42.74′	1.74224	74°35.81′	1.72790
TK119	80°12.12′	1.73989	73°07.74′	1.72394
TF102	57°51.53′	1.66575	54°32.75′	1.64916
TF102	57°38.96′	1.66429	54°33.39′	1.64922

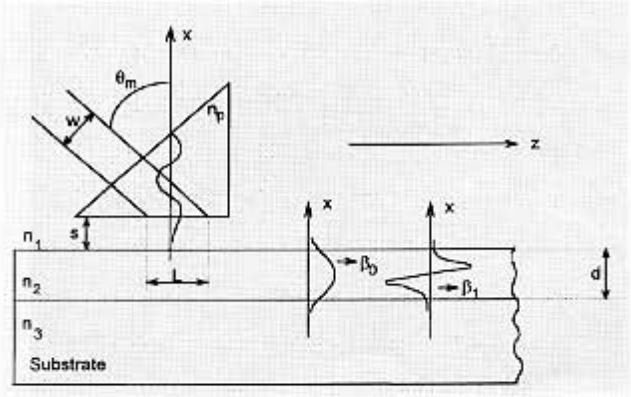

Fig. 2. Diagram of a prism coupler

Table 3. Thin films parameters

Thin film	n	d (Å)
TiO_2	1.922	900
ZnS	2.550	1480
Photoresist	1.578	1337
Polystyrene	1.560	3324

In our case the upper medium of the waveguide was the air so that it is easy to find a prism material with $n_p > n_1$. As shown in Table 1, this condition is fulfilled by all prisms.

The laser beam is totally internally reflected at the $n_p - n_1$ interface, setting up a standing wave mode in the prism. This mode is stationary in the x direction, but moves in the z one, with a phase constant β_p. The various modes which may exist in the waveguide are moving towars z direction with phase constants β_m. If the prism spacing s is small enough then it is a coherent transfer of energy from the prism mode to the m-th waveguide mode, so that $\beta_o = \beta_m$. The phase-match condition gives then:

$$\frac{2\pi n_p}{\lambda_0} \sin\theta_m = \beta_m \tag{2}$$

This phase-match condition implies that:

a) The incidence angle θ_m of the beam to the prism surface must be greater than the critical angle for total internal reflection in the prism:

$$\theta_m > \theta_c = \sin^{-1}\left(\frac{n_1}{n_p}\right) \tag{3}$$

b) The refractive index np of the prism must surpass not only n_1, but n_2 too. Because the waveguide index n_2 is generally close to the substrate index n_3, we have:

$$\beta_m \approx k n_2 = \frac{2\pi}{\lambda_0} n_2 \tag{4}$$

Since $\sin\theta_m \leq 1$ and $\beta_m \geq k n_3$ we obtain that $n_p > n_2$. In the case of glass waveguides, with indices equal to about 1.5, it is easy to find a suitable prism material, with a greater index. However, semiconductor waveguides, which typically have indices about 3 or 4, are more difficult to couple with prisms.

c) The coupling efficiency in this particular case of prism coupling is given by:

$$\eta = \frac{4}{L|T|^2}\left\{1 - e^{\frac{\frac{1}{2}|T|^2}{2d\,\mathrm{tg}\,\theta_m}}\right\} \tag{5}$$

where T is the complex transmission coefficient of the guide, L is the length required for a complete coupling and d is the waveguide thickness.

We can notice that there is a critical angular dependence of coupling efficiency into a given mode so that the incident beam must be highly collimated. Due to this fact, the prism couplers cannot be used efficiently with semiconductor lasers having a beam divergence half-angle of $10^\circ \div 20^\circ$ [1,8].

2.3. Waveguides

Considering the mandatory condition that, for obtaining waveguiding and coupling, the refractive index of the waveguide must be greater than that of the substrate and smaller than that of the prism, it is obvious that the material to be used for the thin guiding layer has to have a refractive index between 1.51 and 1.72 at λ=656 nm (see Tables 1 and 2).

Among the available materials, the polystyrene was the most convenient to use. The method used for obtaining a thin layer was the deposition from solution. The solution was prepared by dissolving the polystyrene in xylene at 100°C. The deposition from solution can be achieved even by applying a solution that dries to form a film and by spinning the substrate to spread the layer evenly or by dipping the substrate into the solution and slowly withdrawing it [1,3,5].

The advantage of these methods is that they are inexpensive and can be applied without any sophisticated equipment.

As the polystyrene solution has a high surface tension coefficient the method was improved by modifying the dipping technique: the glass substrates were first horizontally dipped into solution and then was turned vertically and slowly withdrawn. They were left to dry for 24 hours in a vertical position to obtain a good uniformity. This can be verified when the layer is guiding, by observing if the ray is linear or curved.

Once the thin layers obtained on glass substrates, they must be characterized. The thickness and the refracting indices of the polystyrene layers were determined by ellipsometry. It was used a PCSA setup at an incidence angle of 50°. After obtaining experimentally the ellipsometric quantities Ψ and Δ, the characteristic parameters of the layers (n, d) were obtained using a computer program [9÷11].

The ellipsometric formula used in the case of a transparent, asymmetric waveguide is:

$$\mathrm{tg}\Psi e^{i\Delta} = \frac{r_{p1} + r_{p2}\, e^{-i2\delta}}{1 + r_{p1} r_{p2}\, e^{-2\delta}} \cdot \frac{1 + r_{s1} r_{s2}\, e^{-2\delta}}{r_{s1} + r_{s2}\, e^{-2\delta}} \tag{6}$$

where $\delta = \frac{2\pi}{\lambda} d\,(n_2^2 - n_1^2 \sin^2\varphi_0)^{1/2}$ and r_{p1}, r_{p2}, r_{s1} and r_{s2} are Fresnels coefficients for the reflection at air-film and respectively film substrate interfaces, n_1 is the refractive index of the air, n_2 is the refractive index of the film and φ_0 is the incidence angle, fixed at 50°.

The results for the polystyrene thin films, as well as for other films (TiO_2, ZnS and photoresist) are given in Table 3.

Introducing the results in the Eq. 7 that gives the number of guided modes as a function of the three refractive indices (n_3, n_2, n_1) and of the layer thickness (d), in the case of an asymmetric waveguide (substrate, layer, air),

$$M = \left[\frac{V}{\pi} - \frac{1}{\pi}\arctan\left(\frac{\rho\sqrt{a}}{1+\rho\sqrt{a}}\right)\right] + 1 \tag{7}$$

where $V = d \cdot k\,(n_2^2 - n_3^2)^{1/2}$ is the normalized frequency, $a = \frac{n_3^2 - n_1^2}{n_2^2 - n_3^2}$, and ρ=1 for TE modes or $\rho = \frac{n_2^2}{n_1^2}$ for TM modes.

One can see that for the polystyrene layer, its thickness is greater than that of the cutoff. Accordingly, this layer can be used as a waveguide.

Both TiO_2 and ZnS layers have a refractive index greater than that of prisms and therefore the coupling cannot be realized. For the photoresist layer, the thickness is below that of cutoff and no mode can be guided through such layer.

The next step was to use a prism coupler for introducing a He-Ne laser beam (λ=6328 Å) into the polystyrene waveguide. Because the refractive index of the layer is 1.56 and the

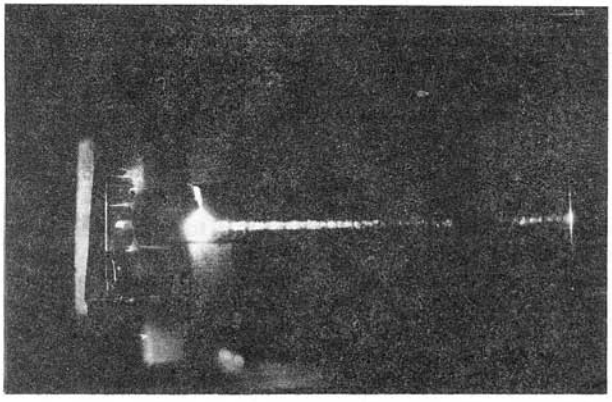

Fig. 3. The input coupling

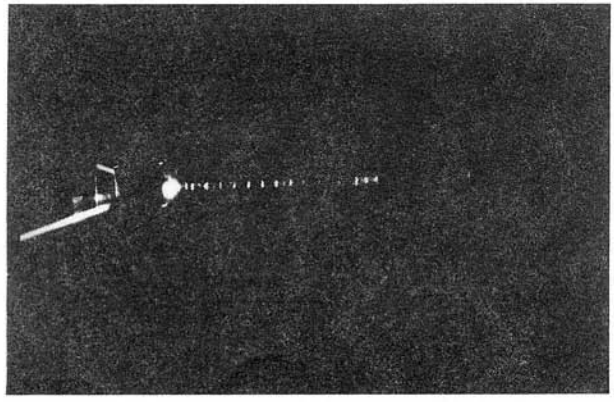

Fig. 4. The output coupling

refractive index of the prism must be greater than that of the layer, only the prism of glass TF119 could be used, with $n_p \approx 1.72$.

The angle of the laser beam, referenced to the normal of the front face of the prism, can be determined from the phase-match condition [1,6,7]. The refraction angle in the waveguide must be greater than the critical angle for total reflection.

The glass plate on which the polystyrene waveguide was obtained was fixed with two metal frames, the coupling prisms being mechanically pressed for obtaining an air spacing small enough for coupling. The input coupling is presented in Fig. 3.

In order to obtain the output coupling, a second prism, identical with the first, was positioned at the end of the waveguide. Using the same mechanical way for pressing the prism, there were extracted from the waveguide $1 \div 4$ modes, depending on the incidence angle of the laser beam on the front face of the input prism. In Fig. 4 one may observe the three modes extracted on the front face of the output prism.

3. Conclusions

We have shown that the polystyrene thin film obtained by deposition from solution can work as a waveguide, with a relatively good uniformity of the thickness.

Further improvements can be expected by hardening the polystyrene thin layer so that when the input coupling prism coupling is pressed, the polystyrene thin film would not be scratched. Due to eliminating this small scratch acting like a diffractive slit which diffracts the incident beam into the glass substrate, the coupling efficiency and the intensity in each guided mode can be improved.

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