A NOVEL TECHNIQUE FOR ANALYSIS AND DESIGN OF DIFFUSED Ti:LiNbO_3 OPTICAL PLANAR WAVEGUIDES

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ABSTRACT:

In this work is presented a new efficient and simple method, which allows the analysis and design of planar optical waveguides. This method links the desired performances of the optical waveguides with basic technological parameters.

The first four charts of the method can easily be adapted for planar waveguides of arbitrary index profile. The last two charts were obtained experimentally and are valid for diffused Ti:LiNbO_3 optical planar waveguides.

The main optical parameters may be easily interrelated utilizing a personal computer or drawing simple vertical and horizontal lines on an abacus.

2.INTRODUCTION

Integrated optics design has been the subject of a great number of studies and experimental works. Over the last two decades, a considerable effort has been put into the design and fabrication of planar optical waveguides, being the LiNbO_3 the most utilized substrate in integrated optics.

In order to have an easy-to-use procedure for planar waveguides design, specially on diffused Ti:LiNbO_3 waveguides, a new design technique has been developed. Its main advantage is the very straight-forward way to obtain the optical and technological parameters, drawing simple vertical and horizontal lines on the charts developed or utilizing a personal computer where the data of the charts can be stored.

A numerical example which illustrates the calculation procedure is also presented.

3. ABACUS DEVELOPMENT

The abacus consists of six normalized charts, as shown in Figure 1. The first four charts were calculated theoretically and the fifth and sixth, experimentally.

As it is known¹, the normalized dispersion equation

$$2V \int_0^{x'_t} [f(x') - b]^{1/2} dx + \phi_c + \phi_t = 2\pi m \quad (1)$$

approximates the resonance condition for a propagating mode, in a planar waveguide of gradual index $f(x')$, where ϕ_c and ϕ_t are the phase changes at the surface ($x' = 0$) and turning ($x' = x'_t$) boundaries points. Both depend on polarization of propagating modes (TE or TM). x' is the normalized coordinate, perpendicular to the crystal surface. If d_z is the diffusion depth, $x' = x/d_z$. b is the normalized effective index:

$$b = (N^2 - n_b^2)/(n_s^2 - n_b^2) \quad (2)$$

where N is the effective index of the mode, and n_b , n_s are substrate and surface indices, respectively.

V is the normalized depth, or normalized frequency of the planar waveguide

$$V = \frac{2\pi}{\lambda} dz (n_s^2 - n_b^2)^{1/2} \quad (3)$$

Because of the value of $f(x'_t)$ at the turning point is

$$f(x'_t) = b \quad (4)$$

equation (1) can be solved numerically for each mode. The resulting normalized curves are given in Figure 1.1 for the first two modes and, for gaussian index profiles².

FIGURE 1

In integrated optical waveguides, electric field transversal component E_y has to satisfy the Helmholtz equation. This equation can be written as a function of the previous normalized parameters V and b . The afore mentioned equation can be numerically solved and the normalized field distribution for each propagation mode is obtained. The normalized mode size

$$\sigma' = \sigma/d_z \quad (5)$$

taken between points where the field mode size decreases to $1/\sqrt{2}$ of its maximum value, is shown to depend on the normalized parameter V .

Figure 1.2 shows this first mode size as a function of the normalized parameter V , for gaussian index profiles.

In Figure 1.3 is represented a new normalized parameter

$$V' = V/d_z \quad (6)$$

which is utilized to link the modal size with the parameters of the normalized frequency V (d_z , λ and $(n_s^2 - n_b^2)^{1/2}$) by means of straight lines.

This relation between the difference of the square surface and substrate (bulk) indices, the new normalized parameter V' , and the wavelength λ ; may be expressed as:

$$\left[V' \frac{2\pi}{\lambda} \right]^2 = n_s^2 - n_b^2 \quad (7)$$

In Figure 2, which includes three more wavelengths than figure 1.4, the values of equation (7) are given for five wavelengths : 0.6328, 0.83, 1.06, 1.32 and 1.55 μm .

Figure 1.5 was obtained only for diffused Ti:LiNbO_3 optical waveguides.

Since the increment in the refractive index in a LiNbO_3 crystal is proportional to the titanium concentration to be diffused into it, for

$\Delta n_s \ll n_b$ we can write that

$$n_s^2 - n_b^2 = C_u(N, \lambda) \cdot (2 \cdot n_b \cdot \tau/dz) = C_u(N, \lambda) \cdot \tau' \quad (8)$$

where C is a value depending on polarization (u), wavelength (λ) and Ti

Fig. 2 : Normalized frequency V' versus square indices difference of the diffused waveguide

waveguide concentration (N) and the Ti film thickness before diffusion (τ). τ' is a new parameter, the normalized titanium thickness.

In order to obtain the coefficient $C_u(N, \lambda)$ we have fabricated and characterized planar waveguides by diffusion of titanium thin films of thickness ranging from 200 Å to 1200 Å, onto z-cut $LiNbO_3$ substrates. The Ti

films were diffused at 996 °C, 1032 °C and 1064 °C. in a wet oxygen atmosphere for canceling the LiO_2 out-diffusion. The thickness of the Ti thin film was measured with a Taly-step (Sloan 3030), that offers a precision of $\pm 40 \text{ \AA}$.

The effective indices for TE and TM modes were measured by the prism method. From the data obtained and additional calculations, a gaussian refractive index profile is observed.

Our results are in good agreement with data reported by Minakata et al.³. The functions given by F.Rottman et al.⁴ and by S.Fouchet et al.⁵, were utilized to calculate the values of $C_u(N,\lambda)$ for TM and TE polarization.

Figure 1.5 has been obtained using those results, which were measured at wavelengths of 0.6328 and 1.32 μm .

Figure 1.6 relates the diffusion depth d_z , with the time t_d and temperature T_d of diffusion. The relations were obtained from our experimental data. Due to the different technological conditions of each fabrication laboratory, the last two charts may suffer slight variations. This last chart is in good agreement with the parameters obtained by Bulmer et al.⁶ for low diffusion temperatures (1000°C), being slightly different for medium (1030 °C) and high temperatures (1060 °C). Our values are, therefore, below Fouchet⁵ ones.

4.A numerical example of the utilization of the technique.

The abacus, that is the graphic representation of the technique, can be used for analysis and/or design of planar optical waveguides of gaussian index profiles, drawing simple vertical and horizontal lines. In order to clarify the above facts, a simple example is given.

4.1.Example:

In order to obtain a single-mode and low-loss diffused Ti:LiNbO₃ optical waveguide at 1.32 μm (TM polarization), fabricated on a z-cut substrate, we can choose a normalized diffusion depth V below cut-off frequency of the second order mode ($V = 3.9$, for example). If the diffusion depth (d_z) is 4 μm , drawing vertical and horizontal straight lines, on the abacus, we obtain the next normalized $V = 3.9$.

* normalized mode size	$\sigma' = 0.72$
* normalized effective index	$b = 0.35$
* normalized index difference	$n_s^2 - n_b^2 = 42.3 \times 10^{-3}$
* normalized thickness	$\tau' = 635 \text{ \AA}$

These results lead directly to the basic optical and technological parameters:

* Mode size	$\sigma = 2.88 \text{ }\mu\text{m}$
* Effective index	$N = 2.1480$
* Thickness of titanium thin film	$\tau = 595 \text{ \AA}$
* diffusion temperature	$T_d = 1032 \text{ }^\circ\text{C}$
* diffusion time	$t_d = 11 \text{ hours}$

If we repeat the design with the same V and polarization, but changing the operation wavelength to $0.6328 \text{ }\mu\text{m}$ and the diffusion depth to $3 \text{ }\mu\text{m}$, we obtain:

* Mode size	$\sigma = 2.16 \text{ }\mu\text{m}$
* Effective index	$N = 2.2032$
* Thickness of titanium thin film	$\tau = 180 \text{ \AA}$
* diffusion temperature	$T_d = 1032 \text{ }^\circ\text{C}$
* diffusion time	$t_d = 6.25 \text{ hours}$

5.CONCLUSIONS

A novel and simple technique for analysis and design of planar waveguides is presented in this paper. It was developed for diffused Ti:LiNbO_3 optical waveguides, but may be adapted for arbitrary refractive index profiles waveguides.

The technique is based on a normalized abacus that consists of six interrelated charts.

The analysis and/or design may be accomplished drawing simple vertical and horizontal lines. The most important parameters, that characterize the waveguide, can be obtained reading the horizontal and vertical intersections with the axes of the charts.