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THE EVALUATION OF SOME PARAMETERS WHICH CHARACTERIZE THE ER^{3+}-DOPED TI:LINBO$_3$ OPTICAL WAVEGUIDE COUPLERS

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În această lucrare sunt prezentate câteva rezultate experimentale şi teoretice privind caracterizarea unui cuplor direcţional fabricat cu ghiduri optice de undă de tip Er^{3+}:Ti:LiNbO$_3$. Pe baza teoriei modurilor cuplate a fost evaluat coeficientul de cuplaj dintre două ghiduri adiacente.

Evaluarea altor parametri care caracterizează dispozitivul menţionat mai sus (raportul puterilor cuplate, lungimea cuplajului perfect, incrementul lungimii efective de interacţie şi indicii de refracţie efectivi) a fost făcută utilizând spectrul în domeniul IR în jurul lungimii de undă de 1530 nm (utilizată foarte mult în telecomunicaţiile optice) şi metoda celor mai mici pătrate.

In this paper we report some experimental and theoretical results concerning the characterization of a directional coupler in Er^{3+}:Ti:LiNbO$_3$ optical waveguides. Based on the mode coupling theory we evaluated the coupling coefficient between two adjacent waveguides of the directional coupler.

The experimental IR transmission spectra of an Er^{3+}:Ti:LiNbO$_3$ directional coupler around 1530 nm (which is widely used in optical telecommunications) and the least-square method were used for the evaluation of some other parameters which define the above mentioned device (e. g. the power coupling ratio, the perfect coupling length, the effective interaction length increment and the effective refractive indices, respectively) was performed.

Keywords: Er^{3+}:Ti: LiNbO$_3$ optical waveguides, directional couplers, power coupling ratio, the perfect coupling length

1. Introduction

The straight and curved Er^{3+}-doped LiNbO$_3$ optical waveguides are widely used for the fabrication of complex integrated optic components such as: waveguided lasers and amplifiers, directional couplers, Mach-Zehnder interferometers, wavelength multiplexers/demultiplexers, high-gain Er^{3+}-doped waveguide amplifiers, optical switches etc. [1]-[5].

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In the last years several theoretical and experimental studies have been reported to characterize the Er^{3+}:Ti:$LiNbO_3$ optical waveguide directional couplers [1]-[3].

In this paper, we propose an original analysis of the coupling coefficient between two adjacent waveguides of the Er^{3+}:Ti:$LiNbO_3$ directional coupler and the evaluation of other parameters which characterize the above mentioned device. Here, we evaluated the power coupling ratio, the perfect coupling length, the effective interaction length increment and the effective refractive indices, respectively using the experimental IR transmission spectra of an Er^{3+}:Ti:$LiNbO_3$ directional coupler around 1530 nm (which is widely used in optical telecommunications) and the least-square method.

The paper is organized as follows: in Sec. 2 we outlined some theoretical considerations concerning the waveguide optical couplers while in Sec. 3 we discussed the experimental and theoretical results obtained in tha case of the above mentioned devices. Sec. 4 is dedicated to the conclusions of this paper.

2. Theoretical considerations

The directional couplers are optical devices which have two input ports and two output ports and is composed of two closely spaced waveguides (Fig. 1).

The working principle of the coupler is based on the periodical optical power exchange that occurs between two adjacent waveguides through the overlapping of the evanescent waves of the propagating modes. By setting design parameters, including waveguide spacing and coupler length, the ratio of powers between the two output ports may be set during the fabrication process to be between zero and 1.

In the case of a directional coupler considering that Ψ_a and Ψ_b describe the optical fields associated with the guided modes of the coupled waveguide system a and b (Fig. 2), they can be expressed as [3]:

$$\Psi_a(x,y,z,t) = A(z)\cdot e^{-i\beta_a z}\cdot F_a(x,y)\cdot e^{-i\omega t} \qquad (1)$$

$$\Psi_b(x,y,z,t) = A(z)\cdot e^{-i\beta_b z}\cdot F_b(x,y)\cdot e^{-i\omega t} \qquad (2)$$

where $A(z)$ and $B(z)$ are the field amplitudes, $\beta_{a,b}$ are the propagation constants and $F_{a,b}(x,y)$ are the field distribution functions which have been normalised to the power flux over the transversal section of the waveguide system (Fig.. 2).

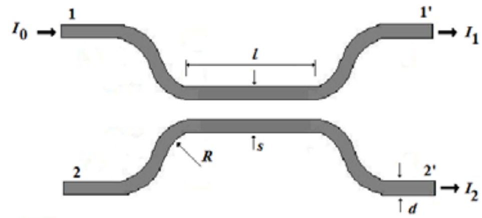

Fig. 1. The schematic representation of the directional coupler.

If the waveguides are close each other, there will exist mutual coupling, and the amplitudes $A(z)$ and $B(z)$ are no longer constant, but will depend on the propagation distance z. The modal coupling equations (3) and (4) involving only two guided modes are reduced to:

$$\pm\frac{dA(z)}{dz} = -i\kappa_{ab}\cdot B(z)\cdot e^{-i(\beta_b-\beta_a)z} \tag{3}$$

$$\pm\frac{dB(z)}{dz} = -i\kappa_{ba}\cdot A(z)\cdot e^{+i(\beta_b-\beta_a)z} \tag{4}$$

where where the coefficients κ_{ab} and κ_{ba} are the coupling coefficients between the modes a and b and vice versa, respectively. The term $e^{\pm i(\beta_b-\beta_a)z}$ corresponds to the *phase mismatching* between the two guided modes.

The coupling coefficient κ_{ab} is calculated according to the following integral:

$$\kappa_{ab}(z) = \frac{k_0^2}{2\beta_a}\frac{\iint F_a^*(x,y)\Delta\varepsilon(x,y,z)F_b(x,y)\mathrm{d}x\mathrm{d}y}{\iint F_a^*(x,y)F_b(x,y)\mathrm{d}x\mathrm{d}y} \tag{5}$$

where $\Delta\varepsilon$ represents the change on the dielectric permittivity induced by the perturbation in the original unperturbed structure (in this case, the change on ε is restricted to waveguide b (Fig. 2).

3. Discussion of the results

Using a laser amplifier as a signal source and the experimental setup presented in paper [6] we measured the IR transmission spectra (1480-1620 nm range) of an Er^{3+}:Ti:$LiNbO_3$ waveguide directional coupler havind 7 μm in width (Fig. 3).

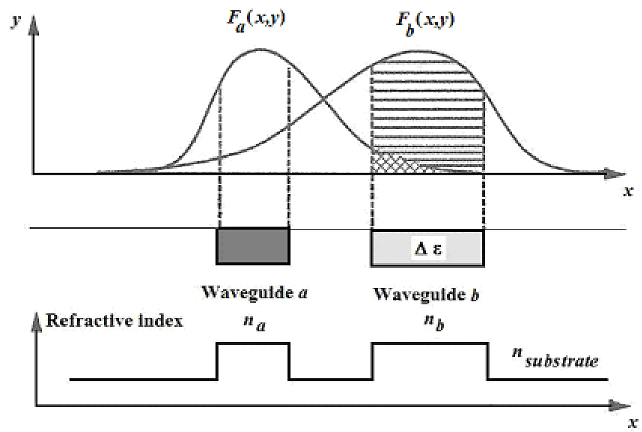

Fig. 2. The coupled waveguides showing the modal field distributions. Dashed area denotes the region where the integration in equation (5) takes place, which is used for obtaining the coupling coefficient.

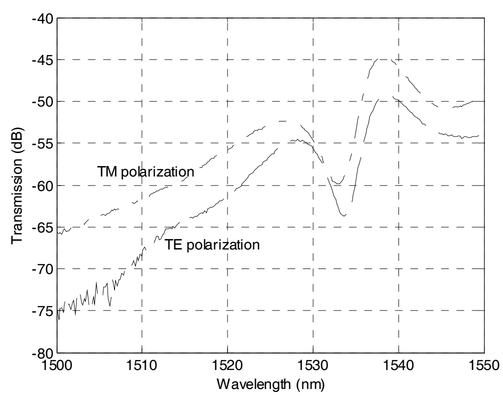

Fig. 3. The IR transmission spectra of an Er^{3+}:Ti:$LiNbO_3$ directional coupler.

Also, using a laser diode emitting at 1.53 μm and an optical fibre as receiver we measured the near field of the above mentioned waveguide for TE and TM polarizations, respectively (Fig. 4).

Based on the experimental results presented in Fig. 4 we used different functions to obtain the best fit of the experimental data in width and depth, respectively defined by the relations:

$$g(x) = \exp\left[-\frac{x^2}{\left(\frac{\sigma_{y,left} + \sigma_{y,right}}{2} + \frac{\sigma_{y\,left} - \sigma_{y\,right}}{2} \right)^2} \right], \tag{6}$$

$$f(y) = \exp\left[-\frac{(y - y_0)^2}{\left(\frac{\sigma_{y,left} + \sigma_{y,right}}{2} sign(y - y_0) + \frac{\sigma_{y\,left} - \sigma_{y\,right}}{2} \tanh(y - y_0) \right)^2} \right]. \tag{7}$$

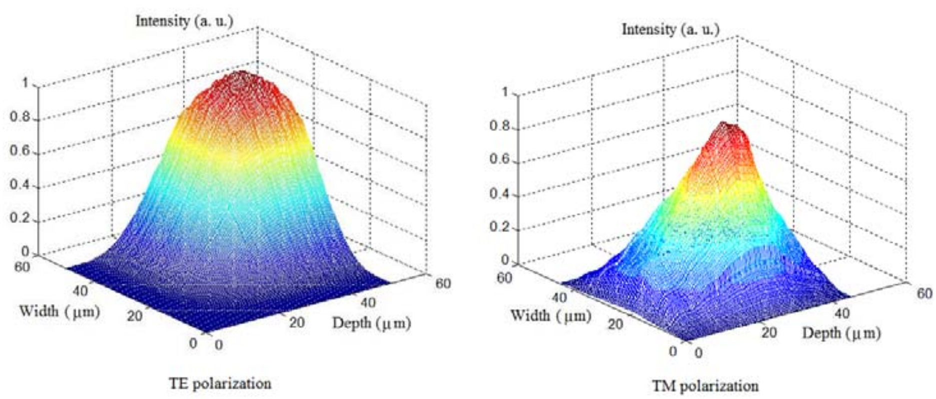

Fig4. The TE and TM near field profiles.

In Eqs. (5), (6) σ_y and σ_x are the corresponding variances of the gaussian functions in width and depth, respectively (Fig. 5).

Taking into account the relation between the refractive index, n and the dielectric constant ε_r, (in particular in dielectric media, the magnetic permeability is very close to that of free space) $n = \sqrt{\varepsilon_r}$ we approximated:

$$\Delta\varepsilon_r = 2 \cdot n \cdot \Delta n\,. \tag{8}$$

Also, considering that the field distribution functions, $F_{a,b}(x, y)$ are obtained from the convolution of the width and depth functions defined by the

Eqs. (6) and (7) in the case of two closed adjacent waveguides having the width of about 7 μ m we obtained for the coupling coeficient (Eq. (5)) the values $\kappa = 2\times 10^{-5}\ \mu m^{-1}$ for TE polarization and $\kappa = 2.1\times 10^{-6}\ \mu m^{-1}$ for TM polarization, respectively.

For the above mentioned value of the waveguide width we eavaluted the coupling coefficient vs the waveguide separation (Fig. 6). In the case the two above mentioned adjacent waveguides are separated b7 μ my we obtained for the coupling coeficient the values $\kappa = 4.2\times 10^{-7}\ \mu m^{-1}$ for TE polarization and $\kappa = 2.5\times 10^{-7}\ \mu m^{-1}$ for TM polarization. For high values of the waveguide separation (i. e. greater than 10 μ m) the coupling coefficient in both polarizations decreases very much.

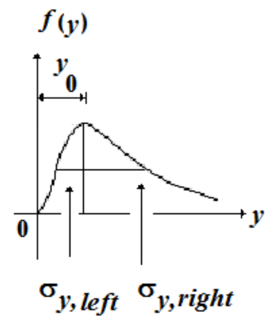

Fig. 5. The variances of the gaussian functions in depth.

Taking into account the transmitted light intensities I_1, I_2 from the two output ports of the device the power coupling ratio can be express by [7], [8]:

$$\eta = \frac{I_2}{I_1 + I_2} = \sin^2\left(\frac{\pi}{2}\frac{l}{L}\right) \tag{9}$$

where L is the perfect coupling length and l the interaction length.

In the case of the directional coupler structure presented in Fig. 1, the interaction at the *S*-curved waveguides is not negligible and therefore Eq. (9) should be replaced by:

$$\eta = \sin^2\left(\frac{\pi}{2}\frac{l+\Delta l}{L}\right) \tag{10}$$

where Δl is the effective interaction length increment due to the *S*-curved waveguides.

For the above mentioned device, in the first step, the experimental data were smoothed and fitted by a fourth order function.

Then, the evaluation of the perfect coupling length, L and the effective interaction length increment, Δl was performed from the dependence of the power coupling ratio, η on the interaction length, l using the least-square method [9].

In the case of a radiation having 1530 nm we obtained the folowing values: $\eta = 0.5285$, $L = 9.99$ μm and $\Delta l = 9.29$ mm.

Using the data from the paper [3] we evaluated the dependence of the output relative power of the directional coupler with losses from the two output ports $P1'$ and $P2'$ on the waveguide length for TE and TM polarizations, respectively the results being presented in Figs. 7 a), b). As can be seen from Figs. 7 a), b) there is a periodically energetic exchange between the adjacent waveguides and the output relative powers decreases exponentially.

4. Conclusions

In this paper we report some experimental and theoretical results concerning the characterization of a directional coupler in Er^{3+}:Ti:$LiNbO_3$ optical waveguides. Based on the mode coupling theory we evaluated the coupling coefficient between two adjacent waveguides of the directional coupler.

Also, we evaluated other parameters which define the above mentioned device: the power coupling ratio, the perfect coupling length, the effective interaction length increment and the effective refractive indices, respectively using the least-square method.

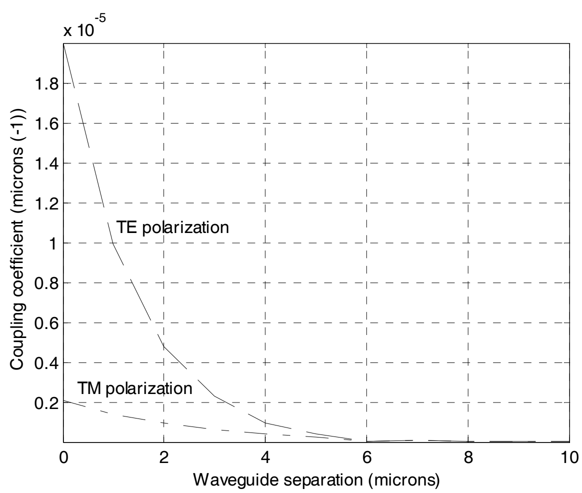

Fig. 6. The coupling coefficient vs the waveguide separation.

The coupling coefficient of the directional coupler with losses vs the waveguide length was also investigated.

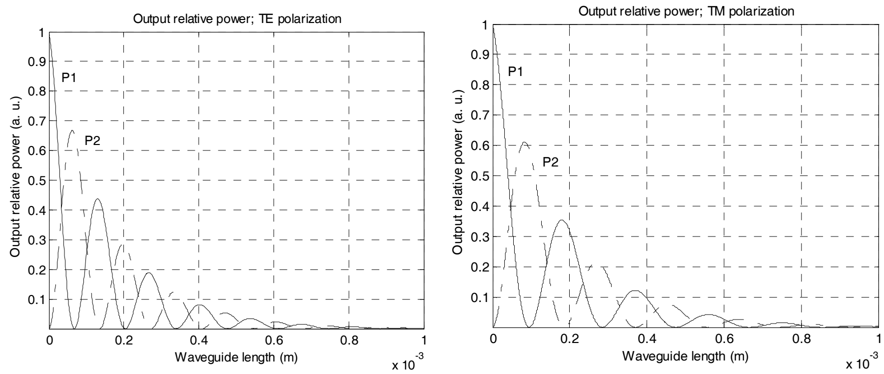

Fig. 7 a), b). The output relative power of the directional coupler with losses on the waveguide length for TE and TM polarizations.

The obtained results are in good agreement with other published in the literature [3] and may be used for the design of complex integrated optoelectronic circuits.

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