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THE THEORETICAL AND EXPERIMENTAL CHARACTERIZATION OF THE Er^{3+}:Ti:LiNbO$_3$ *S*-CURVED OPTICAL WAVEGUIDE COUPLERS

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

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

În acest articol sunt prezentate câteva rezultate teoretice şi experimentale privind caracterizarea unui cuplor direcţional în ghiduri optice curbe-S de tip Er^{3+}:Ti:LiNbO$_3$. Pe baza teoriei modurilor cuplate a fost evaluat coeficientul de cuplaj dintre două moduri adiacente a cuplorului direcţional.

De asemenea, au fost evaluaţi şi alţi parametri care definesc dispozitivul menţionat mai sus, ca: raportul puterilor cuplate, lungimea cuplajului perfect, creşterea lungimii de interacţie effective şi respectiv indicii de refracţie efectivi pe baza celor mai mici pătrate.

Keywords: Directional couplers, Er^{3+}:Ti:LiNbO$_3$ *S*-curved optical waveguides, Power coupling ratio, Perfect coupling length

1. Introduction

During the last years the straight and curved Er^{3+}-doped LiNbO$_3$ optical waveguides were widely used for the fabrication of complex integrated optic components such as: waveguided lasers and high-gain amplifiers, directional couplers, symmetrical and a symmetrical Mach-Zehnder interferometers, wavelength multiplexers/demultiplexers, optical switches etc. [1]-[11]. Nowadays numerous theoretical and experimental studies have been reported to characterize the Er^{3+}-doped Ti:LiNbO$_3$ optical waveguide directional couplers [1]-[3], [6], [9], [10].

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This paper presents an original analysis of the coupling coefficient between two adjacent waveguides of the Er^{3+}:Ti:$LiNbO_3$ *S*-curved directional coupler and the evaluation of other parameters which characterize 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.

In Sec. 2 of the paper 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. The conclusions of this paper are presented in Sec. 4 of this work.

2. Theoretical considerations

The *S*-curved waveguide directional couplers are optical devices which have two input ports $P1$, $P2$ and two output ports $P1'$, $P2'$ and is composed of two closely spaced *S*-curved 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 [3].

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]:

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

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

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.

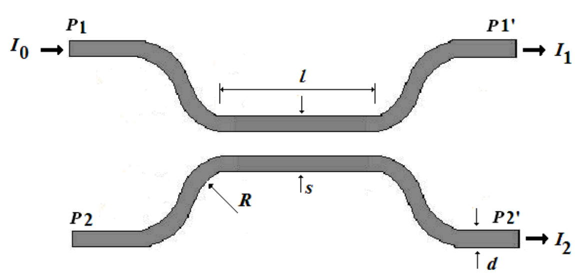


Fig. 1. The schematic representation of the S-curved waveguides directional coupler.

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.

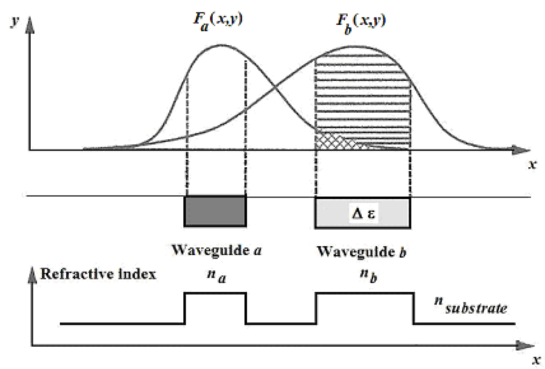


Fig. 2. The coupled waveguides showing the modal field distributions. Dashed area denotes the region where the integration in equation (5) takes place, which is used for obtaining the coupling coefficient.

The coupling coefficient κ_{ab} can be 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 .

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).

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:

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

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

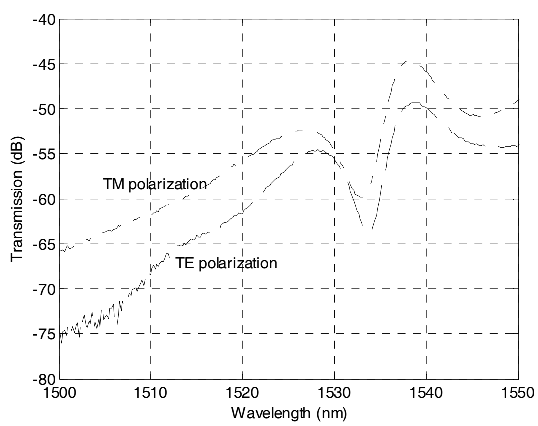


Fig. 3. The IR transmission spectra of an Er^{3+}:Ti:$LiNbO_3$ S-curved waveguides directional coupler.

In Eqs. (6), (7) σ_y and σ_x are the corresponding variances of the gaussian functions in width and depth, respectively.

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:

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

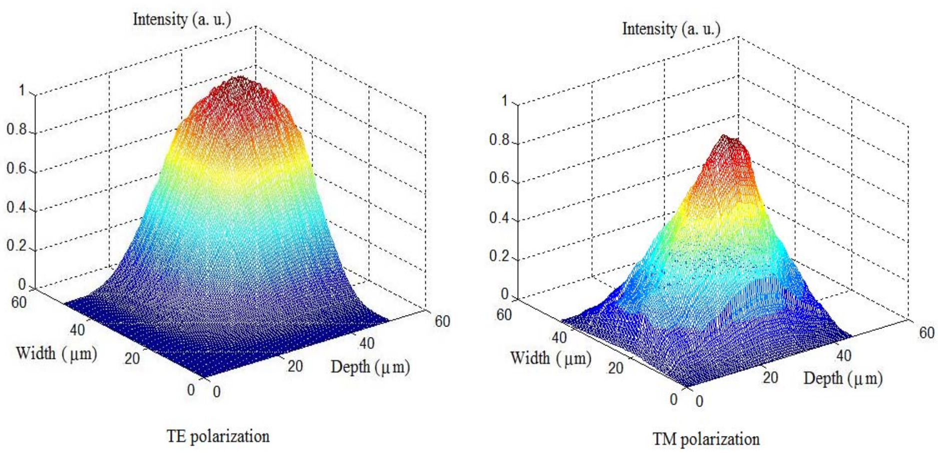


Fig. 4. The TE and TM near field profiles.

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 μm we obtained for the coupling coeficient (Eq. (5)) the values $\kappa = 2 \times 10^{-5}$ μm^{-1} for TE polarization and $\kappa = 2.1 \times 10^{-6}$ μm^{-1} for TM polarization, respectively. For the above mentioned value of the waveguide width we eavaluted the coupling coefficient vs the waveguide separation (Fig. 5). In the case the two above mentioned adjacent waveguides are separated by 7 μm we obtained for the coupling coeficient the values $\kappa = 4.2 \times 10^{-7}$ μm^{-1} for TE polarization and $\kappa = 2.5 \times 10^{-7}$ μm^{-1} for TM polarization. For high values of the waveguide separation (i. e. greater than 10 μm) the coupling coefficient in both polarizations decreases very much.

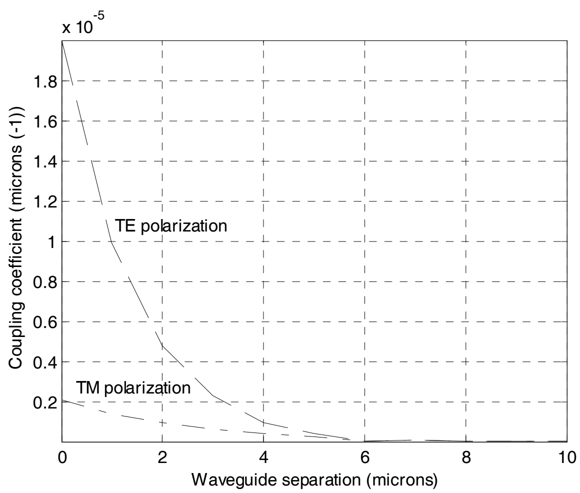


Fig. 5. The coupling coefficient vs the waveguide separation.

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]:

$$\eta = \sin^2[\pi(l + \Delta l)/2L] \tag{9}$$

where L is the perfect coupling length, l the interaction length and 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: η = 0.5285, L = 9.99 μm and Δl = 9.29 mm. Using the data from the papers [3], [6], [9] 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. 6 a), b).

As can be seen from Figs. 6 a), b) there is a periodically energetic exchange between the adjacent waveguides and the output relative powers decreases exponentially.

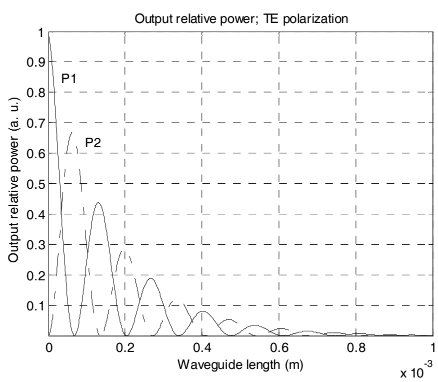
4. Conclusions

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

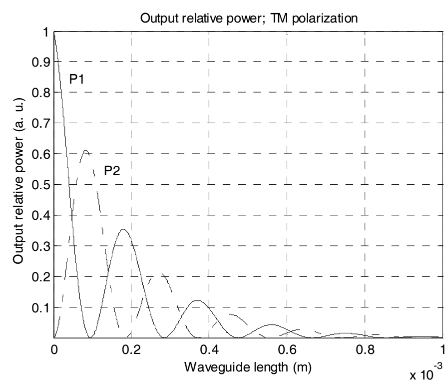
Also, we evaluated other parameters which define the above mentioned device: the power coupling ratio, the perfect coupling length, the effective interaction length increment and the effective refractive indices, respectively using the least-square method.

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

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.



a)



b)

Figs. 6 a), b). The output relative power of the directional coupler with losses on the waveguide length for TE and TM polarizations.

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