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Evaluation of losses and group effective refractive index of Er^{3+}-doped $Ti:LiNbO_3$ optical waveguides

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Based on optical methods in this paper we report some experimental and theoretical results concerning the evaluation of losses and group effective refractive index of Er^{3+}:Ti:$LiNbO_3$ optical waveguides from the transmitted intensity of the Fabry-Pérot optical waveguide resonator. Using interferometric methods in order to obtain the resonances (heating the optical waveguide cavity with a Peltier element and also varying the frequency of a tunable laser) from the experimental data we evaluated the attenuation coefficient for a laser radiation having λ =1.55 μm and also, from the same spectra the group effective refractive index.

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1. Introduction

In the last time the passive and active (doped with Nd^{3+}, Er^{3+}, Yb^{3+} etc. ions) optical waveguides based on lithium and glass substrates have attracted great interest in the field of integrated optics for the devices (optical modulators, switches, filters, lasers, amplifiers, nonlinear optical converters) to be used in high-speed optical communications and sensors. Knowledge of the behaviour of optical waveguides is essential for the fabrication of more complex integrated circuits. One of the parameters which characterize the optical waveguides is the optical attenuation, another one being the group effective refractive index. The measurement of the optical losses plays an important role in the fabrication of high quality active and passive optical waveguides and also in the efficiency of the coupling to the optical fiber or other elements of the optical integrated circuit.

The propagation losses which characterize the optical waveguide quality are determined by the radiation absorption and scattering but also by the nonlinear effects and other factors. For the measurement of the optical losses are utilised the destructive and non-destructive methods. In the last years several papers concern the measurement and evaluation of the losses in the above mentioned optical waveguides [1-5]. Among the non-destructive techniques for the measurement of the optical losses one of the most utilised are the interferometric methods, using the heating the optical waveguide cavity with a Peltier element and also by varying the frequency of a tunable laser in order to obtain the resonances [5-7].

The structure of the paper is the following: in Sect. 2 we present the basic equations used for the evaluation of the optical losses and in Section 3 we report the experimental set-up and discuss the obtained results. The conclusions of the paper are outlined in Section 4.

2. Theory

Based on the theoretical models presented in papers [4]-[6] in the case of small contrast, K of the Fabry-Pérot resonances (Fig. 1)

$$K = \left(I_{\max} - I_{\min}\right)/\left(I_{\max} + I_{\min}\right) \qquad (1)$$

(where $I_{\max}$ and $I_{\min}$ represent the maximum and minimum values of the transmitted intensity) the attenuation coefficient, α is given by the relation:

$$\alpha \sim \frac{4.34}{L}\left(\ln R + \ln 2 - \ln K\right), \qquad (2)$$

R being the mode reflectivity and L the waveguide length. In deriving Eq. (2) it was assumed that K is independent on the incident laser beam intensity and on the coupling efficiency of the waveguide mode.

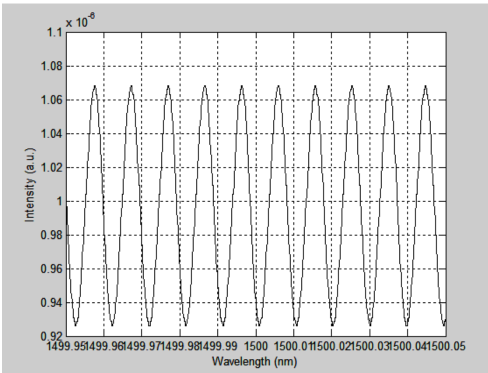

Fig. 1. The optical waveguide transmitted intensity.

An estimation of the absolute error of the attenuation coefficient $\Delta\alpha$ can be computed by differentiating Eq. (2) in the form:

$$\Delta\alpha = \frac{4.34}{L}\frac{|\Delta K|}{K} \quad (3)$$

showing that it depends on the relative error of the contrast measurement.

Assuming that the the attenuation coefficient and the mode reflectivity are not rapidly varying vs the radiation wavelength, λ the period of the symmetrical monomode Fabry-Pérot optical waveguide resonator may be expressed in an optical frequency scale factor, $\Delta\nu_p$ as [4], [5]:

$$\Delta\nu_p = \frac{c}{2L\left(n + \nu\dfrac{dn}{d\nu}\right)} \quad (4)$$

where

$$\Delta\nu_p = \frac{c\Delta\lambda_p}{\lambda^2}. \quad (5)$$

In Eq. (5) $\Delta\lambda_p$ represents the period of the transmittance which is directly measured (Fig. 1). The group refractive effective index, n_g is given by:

$$n_g = n + \nu\frac{\mathrm{d}n}{\mathrm{d}\nu}. \quad (6)$$

Tacking into account Eqs. (4)-(6) the group effective refractive index may be determined in the form:

$$n_g = \frac{\lambda^2}{2L\Delta\lambda_p}. \quad (7)$$

3. Experimental set-up

The experimental arrangement used to measure the attenuation coefficient with the resonator method is shown schematically in Fig. 2. We used a He-Ne laser (λ = 0.63 μm) for alignment and a laser diode (L. D.) at λ = 1.55 μm for the optical signal, coupled together by a 3 dB coupler (C). The losses and the group effective refractive index of some Er^{3+}:Ti:$LiNbO_3$ optical strip waveguides (W) X-cut 48 mm long made by Pirelli-Cavi Laboratories (Milano-Italy) has been evaluated. The waveguides widths range from 5 μm to 9 μm. The resonator method proved to be especially suitable for evaluating the total loss of both polarizations.

The output signal from the waveguides has been detected by connected to the optical spectrum analyzer (O. S. A.) used like a photodiode; The measured data have been acquired by a computer (CO.). By measuring the contrast of the Fabry-Pérot resonances (Fig. 1) it is possible to evaluate a combined loss-reflection factor and thus give an upper limit estimate for the attenuation coefficient. The transmitted intensity varies periodically with the phase difference and can be tuned varying the temperature of the waveguide using a heating Peltier element (O) or the signal frequency using a tunable laser.

The measurement of the emergent light from the waveguide was performed using an standard optical fiber (O. F.) (Fig. 2) directly coupled with a powermeter (POW.). The displacement of the optical fiber mounted on a support was obtained with an electrostrictive actuator controller (E. A. C.) interfaced with computer to register the waveguide field intensity profile in depth and width for TE and TM polarizations selected by the polarization controller (P) and the isolator (I). By measuring the contrast of the Fabry-Pérot resonances (Fig. 1) it is possible to evaluate a combined loss reflection and thus give an upper limit estimate for the attenuation coefficient (Eq. (2)).

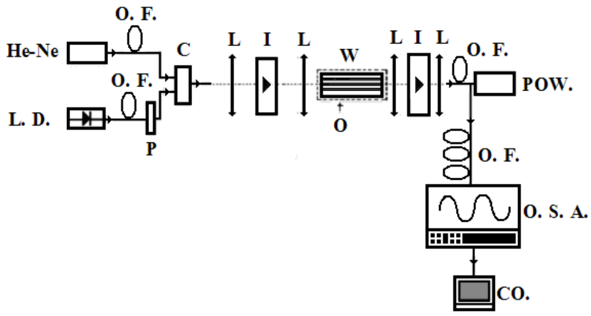

Fig. 2. Schematical experimental set-up for the attenuation coefficient measurement.

In Fig. 3 we present some values of the attenuation coefficient in the case of X-cut Er^{3+}:Ti:$LiNbO_3$ optical strip waveguides for TE (*) and TM (o) polarizations versus the strip widths obtained by varying the temperature of the waveguide, the relative error being $\frac{\Delta\alpha}{\alpha}$~2.5 %. As can be seen from Fig. 3 the attenuation coefficient vs the waveguide width varies nearly linear in the range 5 μm$\div$9 μm for both TE and TM, polarizations respectively, the above mentioned resonances have been obtained also varying the frequency using a tunable laser around the wavelength λ=1.5 μm (fig. 4). As an example for a 5 μm wide X-cut waveguide we have obtained α=0.62 dB/cm ($\frac{\Delta\alpha}{\alpha}$=1.2 %) and α=0.39 dB/cm ($\frac{\Delta\alpha}{\alpha}$=1.4 %) for TE and TM polarizations, respectively. In the case of a X-cut Er^{3+}:Ti:$LiNbO_3$ optical waveguide having the length

L =4.8 cm using Eq. (7) and the spectra presented in Figs. 1 and 4 we obtained for the group effective index n_g =2.343 and respectively n_g =2.279, this values being in good agreement with other published in the literature [4].

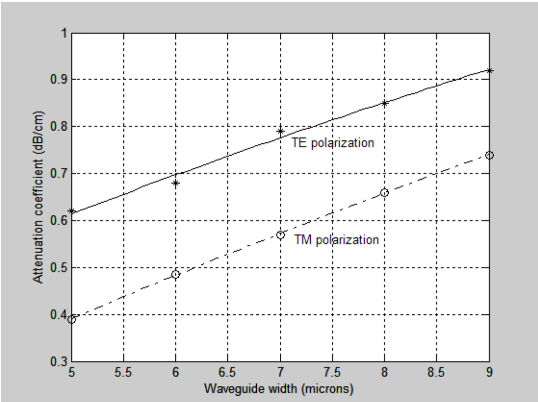

Fig. 3. Losses of X-cut Er^{3+}:Ti:LiNbO$_3$ optical strip waveguides for TE (*) and TM (o) polarizations versus the strip widths at λ = 1.5 µm.

4. Conclusions

Based on interferometric method (Fabry-Pérot optical waveguide resonator) we evaluated the attenuation coefficient of Er^{3+}:Ti:LiNbO$_3$ optical waveguides for a laser radiation having 1.55 µm, which is widely used in optical telecommunications. Also, we evaluated from the same spectra the group effective refractive index. The obtained results are in accordance with others published in the literature [4] and they may be used for the improvement of the optoelectronic integrated components and also for the design of complex integrated circuits.

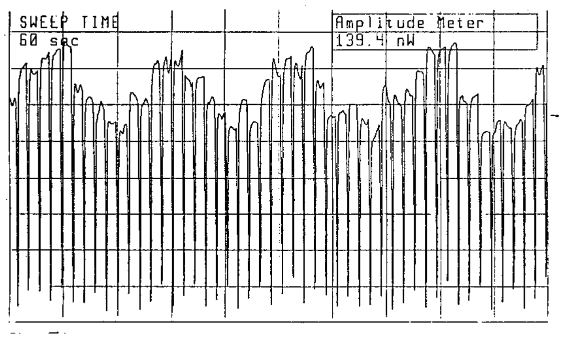

Fig. 4. The resonances obtained by varying the frequency with a tunable laser.

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