LOSSES MEASUREMENT OF Er^{3+}:Ti:LiNbO$_3$ OPTICAL WAVEGUIDES

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Pe baza metodelor optice în această lucrare se prezintă câteva rezultate experimentale privind măsurarea pierderilor în ghidurile optice de undă de tip Er^{3+}:Ti:LiNbO$_3$. Utilizând o metodă interferometrică (cea a rezonatorului Fabry-Pérot) am evaluat coeficientul de atenuare în cazul unei radiaţii laser cu λ =1.55 μm. De asemenea, am evaluat pierderile: la inserţie, cele dependente de polarizare precum şi cele corespunzătoare cuplajului cu exteriorul.

Based on optical methods in this paper we report some experimental results concerning the losses measurement of Er^{3+}:Ti:LiNbO$_3$ optical waveguides. Using interferometric method (Fabry-Pérot optical waveguide resonator) we evaluated the attenuation coefficient for a laser radiation having λ =1.55 μm. Also, we evaluated the insertion, polarization dependent and coupling with the external losses.

Keywords: Er^{3+}:Ti:LiNbO$_3$ optical waveguides, attenuation coefficient, insertion loss, polarization depending loss.

1. Introduction

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. 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.

There are several types of losses. The propagation losses which characterize the optical waveguide quality are determined by the radiation

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absorption and scattering but also by the nonlinear effects and other factors. The evolution of polarization along an optical waveguide is of a completely statistical nature and, in consequence is totally unpredictable. Generally the polarization state being not maintained along the optical waveguide this behaviour determines the polarization dependent losses which have many sources: dichroism, waveguide bending, angled optical interfaces and oblique reflection. The insertion losses are related to the polarization losses which determine isolation or cross talk. In the case of active optical waveguides (lasers, amplifiers) one must take into account also the losses due to the coupling of the radiation with the external which are determined by the reflectivities of the end faces of the devices.

For the measurement of the optical losses are used 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 used is the interferometric method [5]-[7].

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

2. Theoretical considerations

Based on the model presented in papers [5], [6] the transmitted intensity I_T of a symmetrical monomode Fabry-Pérot optical waveguide resonator is:

$$I_T = \frac{T^2 \exp(-\alpha L)}{\left(1-\tilde{R}\right)^2 + 4\tilde{R}\sin^2(\Phi/2)} I_0 \eta , \tag{1}$$

where: I_0 is the incident laser beam intensity, η is the coupling efficiency of the waveguide mode, T the end face mode transmissivity,

$$\tilde{R} = R\exp(-\alpha L) , \tag{2}$$

R being the mode reflectivity and α the attenuation coefficient of the optical waveguide having the length L. The internal phase difference at the output $(z = L)$ is:

$$\Phi(L) = k_0 n_{eff} L \text{ , assuming } n_{eff} = \text{constant} . \tag{3}$$

For small contrast K of the Fabry-Pérot resonances

$$K = \left(I_{\max} - I_{\min}\right)/\left(I_{\max} + I_{\min}\right) \tag{4}$$

(where K is independent of I_0 of and of η) the attenuation coefficient, α is given by the relation:

$$\alpha \sim \frac{4.34}{L}\left(\ln R + \ln 2 - \ln K\right). \tag{5}$$

An estimation of the absolute error of the attenuation coefficient $\Delta\alpha$ can be computed by differentiating Eq. (5) in the form:

$$\Delta\alpha = \frac{4.34}{L}\frac{|\Delta K|}{K} \tag{6}$$

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

The polarization dependent losses are a measure of the peak-to-peak difference in transmission of the optical waveguide with respect to all possible states of polarization. It is the ratio of the maximum, $P_{\max}$ and the minimum, $P_{\min}$ transmission of the optical waveguide with respect to all polarization states (Fig. 1). As can be seen from the Fig. 1 the polarization of the constant and fully polarized input signal is varied.

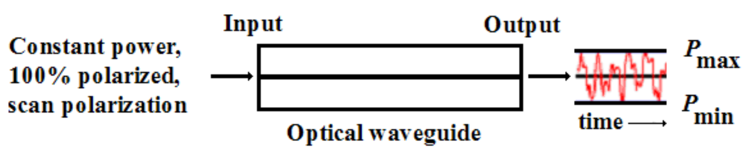

Fig. 1. Polarization dependent loss.

The output power variation is the result of the variation in the polarization of the incident light wave signal.

The polarization dependent loss, (PDL) is defined as [8]:

$$PDL = 10\log\left(\frac{P_{\max}}{P_{\min}}\right), \tag{7}$$

while the insertion loss, (IL) is:

$$IL = -10\log\left(\frac{P_{out}}{P_{inp}}\right) \tag{8}$$

where P_{out} and P_{inp} represent the output and input powers, respectively of the optical waveguide. The sign $(-)$ makes always positive values for propagation losses in the case of passive components. These losses depend on the polarization state of the light which passes through the optical waveguide.

Taking into account Eq. (8) the polarization dependent loss may be defined in the form:

$$PDL = IL_{\max} - IL_{\min} \tag{9}$$

as the difference between the maximum, IL_{max} and the minimum, IL_{min} insertion loss measured by scanning all the polarization states of input light.

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 ($\lambda = 0.63$ μm) for alignment and a laser diode (L. D.) at $\lambda = 1.55$ μm for the optical signal, coupled together by a 3 dB coupler (C). The losses of some Er^{3+}:Ti:$LiNbO_3$ optical strip waveguides (W) X-cut 48 mm long and Z-cut 52 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.

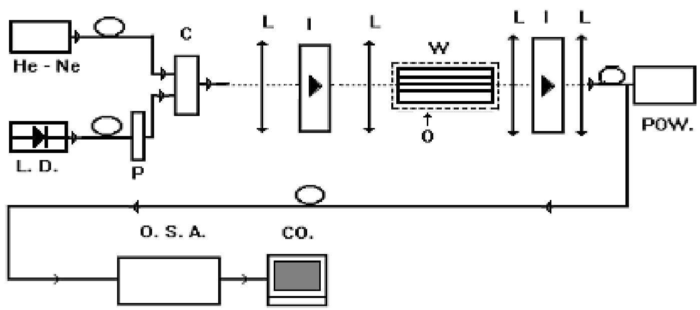

Fig. 2. Schematical experimental set-up for the attenuation coefficient measurement.

The output signal from the waveguides has been detected by an optical spectrum analyzer (O. S. A.) used like a photodiode; then the measured data have been acquired by a computer (CO.). By measuring the contrast of the Fabry-Pérot resonances (Fig. 3) it is possible to evaluate a combined loss-reflection factor and thus give an upper limit estimate for the attenuation coefficient. In Eq. (1) 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 (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).

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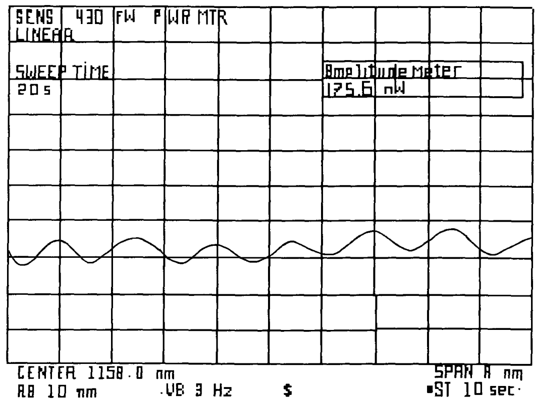

Fig. 3. The optical waveguide transmitted intensity.

In Fig. 4 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. 4 the attenuation coefficient vs the waveguide width varies nearly linear in the range 5 μm $\div$ 9 μm for both TE and TM, respectively polarizations.

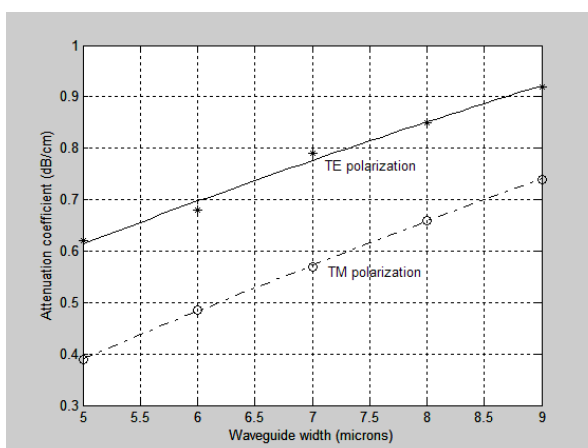

Fig. 4. Losses of X-cut Er^{3+}:Ti:$LiNbO_3$ optical strip waveguides for TE (*) and TM (o) polarizations versus the strip widths at λ = 1.5 μm.

The above mentioned resonances have been obtained also varying the frequency using a tunable laser around the wavelength λ=1.5 μm (fig. 5). 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.

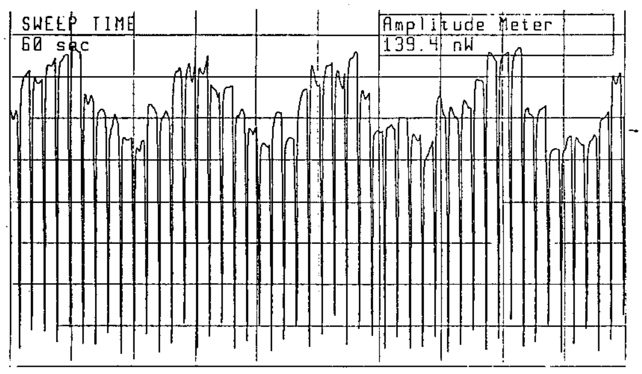

Fig. 5. The resonances obtained by varying the frequency with a tunable laser.

Using a laser radiation having λ=1.3 μm in the case of a 5 μm width X-cut waveguide we obtained α=0.17 (dB/cm) for TE polarization, ($\frac{\Delta\alpha}{\alpha}$=2%) and α=0.12 (dB/cm) for TM polarization, ($\frac{\Delta\alpha}{\alpha}$=4.3%).

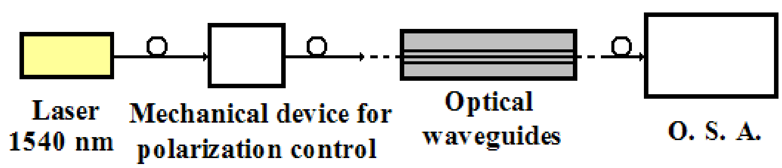

Fig. 6. The experimental set-up for the measurement of the polarization dependent loss.

Based on the principle outlined in Sect. 2 of the paper in Fig. 6 the experimental set-up for the measurement of the polarization dependent loss is presented. The laser radiation (λ=1540 nm) after being controlled polarized by a mechanical device excite the optical waveguides and the output signal from the waveguides has been detected by an optical spectrum analyzer (O. S. A.)

The transmission of each optical component is dependent on the polarization. In Fig. 7 the optical spectrum of a 7.5 μm width and 54 mm length

X-cut Er^{3+}:Ti:$LiNbO_3$ optical waveguide is presented. In this case the maximum optical power was 7.77 dBm.

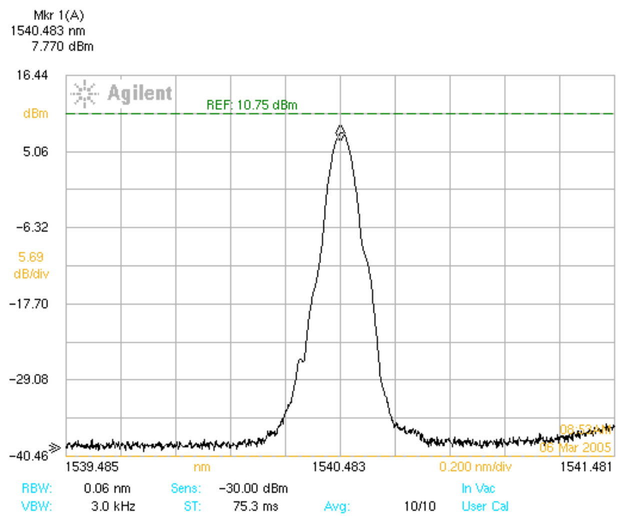

Fig. 7. The optical spectrum of a 7.5 μm width and 54 mm length X-cut Er^{3+}:Ti:$LiNbO_3$ optical waveguide.

In order to evaluate the insertion losses for the Er^{3+}:Ti:$LiNbO_3$ optical waveguides we characterized first the fiber-to-fiber coupling obtaining the following mean value for the power: $P_{med} = 10.66[\text{dBm}]$ and insertion losses, respectively: $IL = 2.89$ [dBm].

Some experimental values of the polarization dependedent losses in the case of the fiber-to-fiber coupling are presented in Table 1, the mean value being $PDL \cong 0.09$ [dBm].

For fiber-to-waveguide coupling we have used the technique illustrated in Fig. 8.

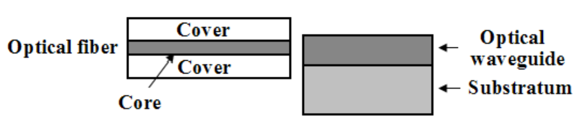

Fig. 8. The fiber-to-waveguide coupling.

As can be seen from the figure the core of fiber must be aligned with carefully to optical waveguide. Thus, in the case of a 7.5 μm width X-cut Er^{3+}:Ti:$LiNbO_3$ optical waveguide we have obtained $IL = 2.89$ [dBm].

Table 1.

No. crt.	P_{max} [dBm]	P_{min} [dBm]	*PDL* [dBm]
1	10.275	10.172	0.103
2	10.951	10.881	0.067
3	10.302	10.187	0.115
4	10.860	10.755	0.105
5	10.937	10.870	0.070

In Tables 2 and 3 the insertion and polarization dependent losses for 54 mm length and several widths X-cut Er^{3+}:Ti:$LiNbO_3$ optical waveguides and for 50 mm length and several widths X-cut Ti:$LiNbO_3$ optical waveguides are presented.

Table 2.

Er^{3+}:Ti:$LiNbO_3$ waveguide width [μm]	*IL* [dBm/cm]	*PDL* [dBm]
5	0.908	0.718
5.5	0.880	0.969
6	0.726	0.855
6.5	0.712	0.888
7	0.675	1.190
7.5	0.613	0.809
8	1.203	0.441
9	0.711	1.375
10	0.756	1.911

Table 3.

Ti:$LiNbO_3$ waveguide width [μm]	*IL* [dBm/cm]	*PDL* [dBm]
5	0.789	0.243
5.5	0.184	0.708
6	0.134	0.800
6.5	0.204	0.819
7	0.251	0.529
7.5	0.167	0.260
8	0.107	0.436
9	0.095	0.774
10	0.126	1.079

As can be seen from tables 2 and 3 the insertion and polarization dependent losses of Er^{3+}:Ti:$LiNbO_3$ optical waveguides are greater than those of Ti:$LiNbO_3$ optical waveguides.

The losses due to the coupling of the radiation with the external, α_e may be calculated using the formula:

$$\alpha_e = -\frac{1}{2L}\ln(R_1 R_2) \tag{10}$$

where L represents the waveguide length and $R_{1,2}$ are the reflectivities of the end faces. In the case of an optical waveguide for which the reflectivities are the same, $R_1 = R_2 = R = \left(\frac{n-1}{n+1}\right)^2 = 0.14$, n being the refractive index of the substrate (like for the waveguides above mentioned) one obtained α_e=0.36 dB/cm (L=5.4 cm).

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 the insertion, polarization dependent and coupling with the external losses. The insertion and polarization dependent losses of Er^{3+}:Ti:$LiNbO_3$ optical waveguides are greater than those of Ti:$LiNbO_3$. The obtained results are in good agreement with others obtained using different methods for measurement [4], [6], [8] and they may be used for the improvement of the optoelectronic integrated components and also for the design of complex integrated circuits.

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