EVALUATION OF THE OPTICAL COUPLING BETWEEN OPTICAL FIBRES AND Er^{3+}:Ti:$LiNbO_3$ OPTICAL WAVEGUIDES

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In this paper we report some experimental and theoretical results concerning the characterization of the coupling between graded refractive-index optical fibres and also between optical fibres and Ti:$LiNbO_3$ and Er^{3+}:Ti:$LiNbO_3$, respectively optical waveguides for λ=1.55 μm using nondestructive methods. We evaluated the coupling loss coefficients between the above mentioned components by approximating the field profile with appropriate Gaussian functions. The refractive-index profiles of the Er^{3+}:Ti:$LiNbO_3$ optical waveguides has been determined from near field intensity measurement using a standard optical fibre as receiver and also a CCD camera. Using the Helmholtz scalar equation and an original deconvolution procedure we evaluated some parameters which characterize Er^{3+}:Ti:$LiNbO_3$ waveguides: the refractive-index difference and the penetration depth.

În această lucrare se prezintă câteva rezultate experimentale şi o analiză teoretică privind caracterizarea cuplajului dintre fibrele optice cu indice de refracţie gradat, dar şi dintre fibrele optice şi ghidurile optice de undă de tip Ti:$LiNbO_3$ şi respectiv Er^{3+}:Ti:$LiNbO_3$ la lungimea de undă λ=1.55 μm utilizând metode nedistructive. Coeficienţii de pierderi dintre componentele menţionate mai sus au fost evaluaţi aproximând profilul câmpului prin funcţii de tip Gauss. Profilurile indicilor de refracţie ale ghidurilor optice de undă de tip Er^{3+}:Ti:$LiNbO_3$ din măsurători de câmp apropiat au fost determinate utilizând ca receptor atât o fibră optică standard cât şi cu ajutorul unei camere CCD. Utilizând ecuaţia Helmholtz şi o

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procedură de deconvoluție originală au fost evaluați și câțiva parametrii care caracterizează ghidurile optice de undă de tip Er^{3+}*:Ti:LiNbO*$_3$ *ca: diferența indicelui de refracție și adâncimea de pătrundere.*

Keywords: coupling loss, optical fibres, Er^{3+}:Ti:$LiNbO_3$ optical waveguides, refractive-index profile, near field.

1. Introduction

Over the last years many theoretical and experimental papers concerning the characterization of the coupling between optical fibres and optical fibres and optical waveguides using nondestructive methods were reported due to their potential use in the fabrication of optical sensors and other optoelectronic integrated circuits [1]-[3]. The exact knowledge of the field distribution and the refractive-index profile are very important for the characterization of the optical fibre circuits.

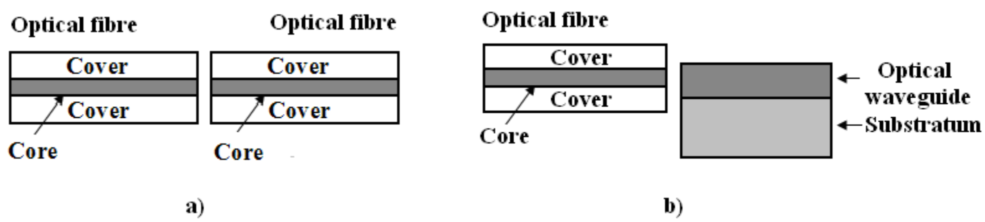
The refractive-index profile of the optical fibres characterized by a graded index profile and of the Er^{3+}:Ti:$LiNbO_3$ optical waveguides has been determined from near field intensity measurement using a standard optical fibre as receiver but also using a CCD camera. An original deconvolution algorithm for the original mode field of the waveguide reconstruction has been used. Using the reported model we evaluated some parameters which characterize Er^{3+}:Ti:$LiNbO_3$ waveguides: the refractive-index difference, Δn and the penetration depth, d [2], [4], [5].

The paper is organized as follows: in Sect. 2 we present some theoretical considerations concerning the basic theoretical notions used for the evaluation of the refractive-index profile reconstruction from deconvolved near field scanning measurement. Sect. 3 is devoted to the experimental techniques used for measurements and to the discussion of the obtained results. In Sect. 4 we outlined the conclusions of this paper.

2. Theoretical considerations

For fundamental mode fibre-to-fibre and fibre-optical waveguide perfect coupling no beam quality is lost. Beside errors in the alignment, coupling loss can be caused by scattering at the waveguide surface. In this case the solution is either the polishing of the end facets of the waveguide or the use of index matching oil. In our measurements we used the index matching oil. It is important to consider that coupling loss occurs at both the waveguide end facets and to distinguish between propagation loss and coupling loss.

The principle of coupling end fibre-optical waveguide is present in Figs. 1 a), b). As can be seen from Fig. 1 the core of fibre must to be aligned with de optical waveguide.



Figs. 1 a), b). a) The fibre-to-fibre coupling, b) the end fibre-optical waveguide coupling.

The coupling loss has been calculated by a numerical evaluation of the overlap integral of the fibre and waveguide mode profiles and is given by the equation [1]:

$$\eta = \frac{\left| \int\int_{-\infty}^{+\infty} F(x,y) W(x,y) dxdy \right|^2}{\int_{-\infty}^{+\infty} |F|^2 dxdy \int_{-\infty}^{+\infty} |W|^2 dxdy}, \quad (1)$$

where F and W are the electric-field distributions of the fibre and the waveguide, x is normal to the direction of propagation in the plane of the substratum and y is normal to the substratum surface (Fig. 2).

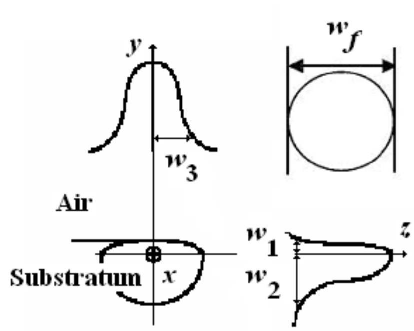


Fig. 2. The fibre mode profile dimension (w_f) and waveguide mode profile dimensions (w_1, w_2, w_3).

Single-mode fibre can be approximated by a circular Gaussian function:

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

where $w_f/2$ is the radius at which the fibre mode field amplitude is equal to $1/\mathrm{e}$. The waveguide mode profile is expressed by the combination of two half-Gaussians in the depth direction:

$$W(x,y) = f(x)\cdot g(y), \tag{3}$$

where:

$$f(x) = F_0 \exp\left(-\frac{x^2}{w_3^2}\right) \text{ and } g(y) = \begin{cases} G_0 \exp\left(-\frac{y^2}{w_1^2}\right), y \le 0 \\ G_0 \exp\left(-\frac{y^2}{w_2^2}\right), y \ge 0. \end{cases} \tag{4}$$

Taking into account Eqs. (2)-(4) the coupling loss (Eq. (1)) can be expressed in terms of the modal parameters as:

$$\eta = \frac{4\left[\left(\frac{1}{w_f^2}+\frac{(1+b)^2}{w_d^2}\right)^{-\frac{1}{2}}+\left(\frac{1}{w_f^2}+\frac{(1+b)^2}{b^2 w_d^2}\right)^{-\frac{1}{2}}\right]^2}{a\left(w_d^2+\frac{4}{a^2}w_f^2\right)}, \tag{5}$$

where: $a = \frac{2w_3}{w_1+w_2}$ is the waveguide mode eccentricity, $b = \frac{w_1}{w_2}$ is the waveguide mode asymmetry, $w_d = w_1 + w_2$ is the depth of waveguide mode.

The most important advantages of refractive-index profile reconstruction from the near field measurement method are: the measurement method is direct, nondestructive and the single-mode optical guide is characterized at the operating wavelength. The major disadvantage is that the near field measurements are affected by many sources of errors, such as noise, errors due to the detection system, nonideal focusing, etc. This imposes the necessity to filter the experimental data of the near field measurements before to use them to determine the refractive-index profile.

In the scalar approximation the field is transversal and completely described by the linearly polarized mode, solution of the Helmholtz scalar equation:

$$\Delta_T \psi(x,y) + \left[k_0 n^2(x,y) - \beta^2\right]\psi(x,y) = 0, \tag{6}$$

where Δ_T is the traverse Laplace operator, $\psi(x, y)$ represents the transverse electric or magnetic field, $n(x, y)$ is the refractive-index profile, β is the propagation constant and k_0 is the wave vector of the vacuum.

The refractive-index profile may be determined from Eq. (6) as:

$$n(x, y) \approx \left(\frac{\beta}{k_0}\right) - \frac{1}{2n_s k_0^2} \frac{\Delta_T \psi(x, y)}{\psi(x, y)}. \qquad (7)$$

In the case of a separable transversal field $\psi(x, y) = \psi(x)\psi(y)$ and assuming that the local field is known $I(y) = \psi^2(x_0, y)$ for a fixed position $x = x_0$ one obtained:

$$n(x_0, y) \approx \left(\frac{\beta}{k_0}\right) - \frac{1}{2n_s k_0^2} \frac{1}{\sqrt{I(y)}} \frac{d^2\sqrt{I(y)}}{dy^2}. \qquad (8)$$

The accuracy of the refractive-index profile reconstruction has been improved by using a deconvolution algorithm of the measured data [2]-[4].

3. Experimental results

Using the experimental arrangement presented in Figs. 3 and 4 a), b) we measured the near field intensity of an optical fibre and of an Er^{3+}:Ti:$LiNbO_3$ 7.5 μm width and 52 mm long X-cut waveguide, respectively using a standard optical fibre (Fig. 4 a)) as receiver and also a CCD camera (Fig. 4 b)).

We used a He-Ne laser (λ = 0.63 μm) for alignment and a laser diode (L. D.) with λ = 1.55 μm as light source, coupled together by a 3 dB coupler (C), at λ=1.55 μm (Fig. 3 and 4 a)). The displacement of the standard optical fibre mounted on a support was performed using an electrostrictive actuator controller (E. A. C.) and a computer program which permitted the registering of the waveguide modes intensity profiles in depth (y) and (x) width for TE and TM polarizations selected by the polarization controller (P) and the isolator (I).

In Fig. 4 b) the light from the laser diode (L. D.) is injected into the optical waveguide using an optical cable smf28 having $w_f = 5.61$ μm and the mode profile at output of the optical waveguide is magnified through a 20x microscope objective (with numerical aperture $N.A. = 0.4$) and acquired using a CCD camera (Hamamatsu Infrared Vidicon). Because we used this type of camera for to acquire the fundamental mode image we must correct the measured intensity. Thus, the field intensity $I(x, y)$ is calculated from the measured intensity $I'(x, y)$ and the nonlinearity coefficient γ of the vidicon camera using the relation:

$$I(x,y) = I'(x,y)^{\frac{1}{\gamma}} . \tag{9}$$

The value of the nonlinearity coefficient is 0.6 for the device used in our work.

The dimension of the acquired image depends on the objective magnification and the distance between the objective and the infrared vidicon camera. Taking into account by the distance between the microscope objective and camera the conversion factor pixel/μm has been determined by calibration with a reference object, a small ruler etched into a silica glass with pitch 2 μm. The data acquisition has been performed using LabView 7.0 program from National Instruments.

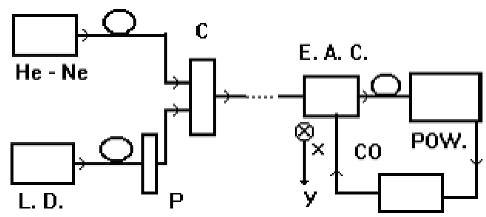
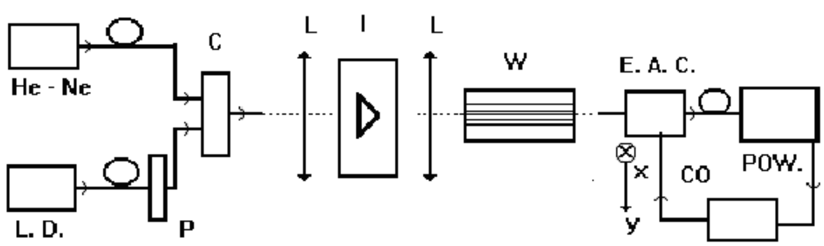
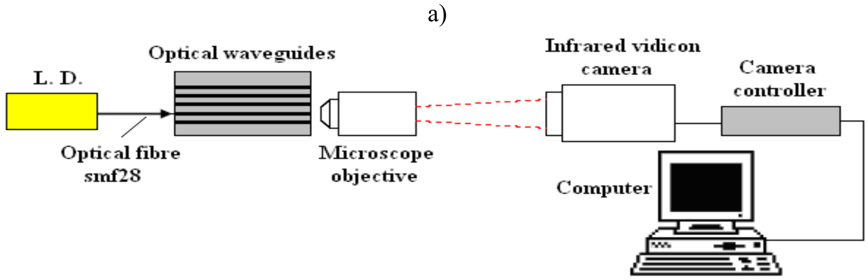


Fig. 3. Schematical experimental setup for the near field measurement in the case of an optical fibre.



a)



b)

Figs. 4 a), b). Schematical experimental setup for the near field measurement using: a) a standard optical fibre and b) a CCD camera.

In Fig. 5 the near-field image of the fundamental mode in a X-cut Er^{3+}:Ti:$LiNbO_3$ waveguide with a 5 μm width and 54 mm length is presented.

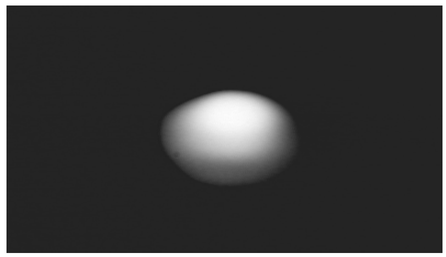


Fig. 5. Near-field image of the fundamental mode in a Er^{3+}:Ti:$LiNbO_3$ waveguide.

Using the experimental arrangement presented in Figs. 3 and 4 a) we measured the near field intensity of an optical fibre characterized by a graded refractive index and also of an Er^{3+}:Ti:$LiNbO_3$ 7.5 μm width and 52 mm long X-cut optical waveguide.

In Fig. 6 the processed field two-dimensional distribution of the graded refractive-index optical fibre using circular Gaussian function (Eq. 2) is presented.

Based on the model presented above and using the determined experimental data we evaluated the coupling coefficient in the case of two graded refractive-index optical fibers obtaining the value η =87.31%.

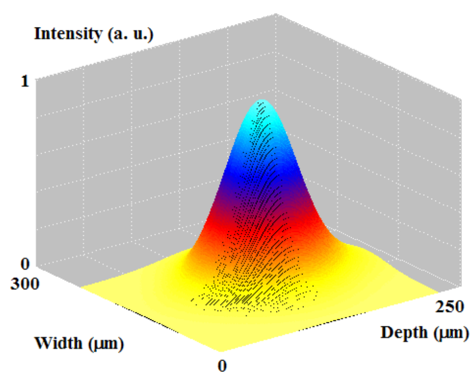
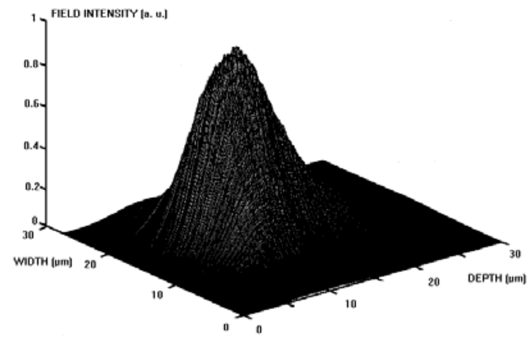


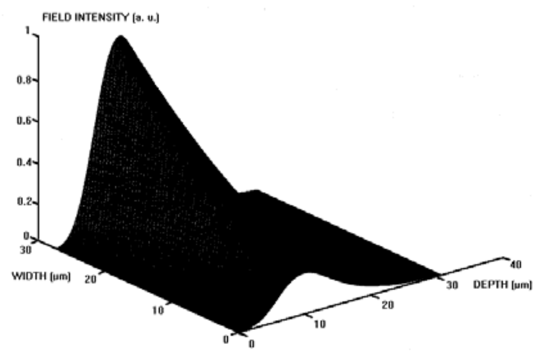
Fig. 6. The processed field two-dimensional distribution of the graded index optical fibre.

The measured field two-dimensional distribution using a standard optical fibre (in the width and the depth of the above mentioned Er^{3+}:Ti:$LiNbO_3$

waveguide) is presented in Fig. 7 a) while in Fig. 7 b) is presented the same distribution after the application of the deconvolution procedure presented in papers [2], [4], [5].



a)

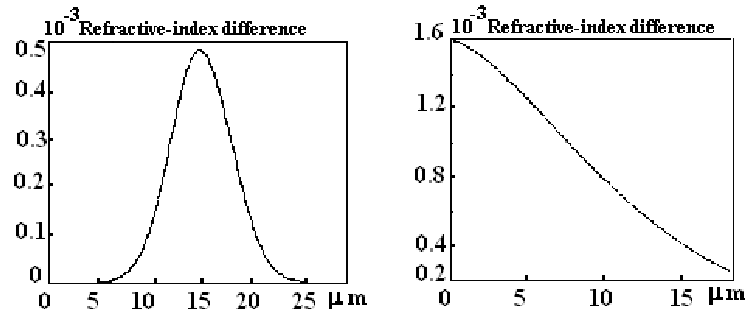


b)

Figs. 7 a), b). a) The measured using a standard optical fibre and b) the deconvolved field two-dimensional distribution for TE polarization.

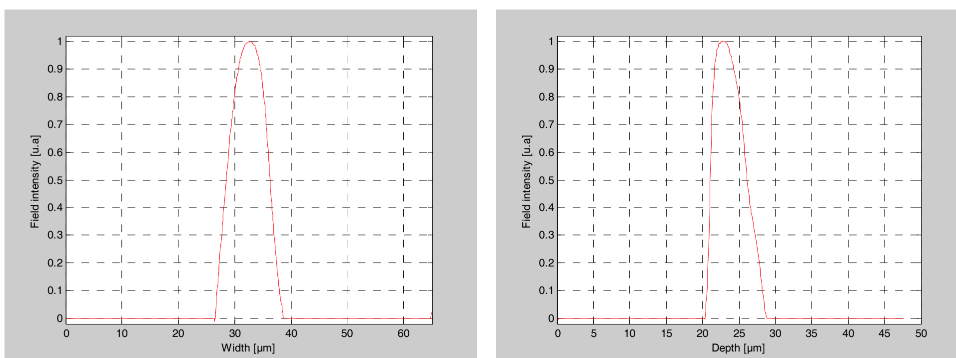
After the performing of the deconvolution procedure we obtained the width and the depth refractive-index profiles (Figs. 8 a), b).

From the refractive-index profiles we obtained for the width refractive-index difference the value $\Delta n = 1.2 \times 10^{-3}$ and for the penetration depth d_x = 3.5 μm while in depth the corresponding values are $\Delta n = 1.08 \times 10^{-3}$ and d_y = 6.5 μm, respectively with an error of about 3.2%.



a) b)

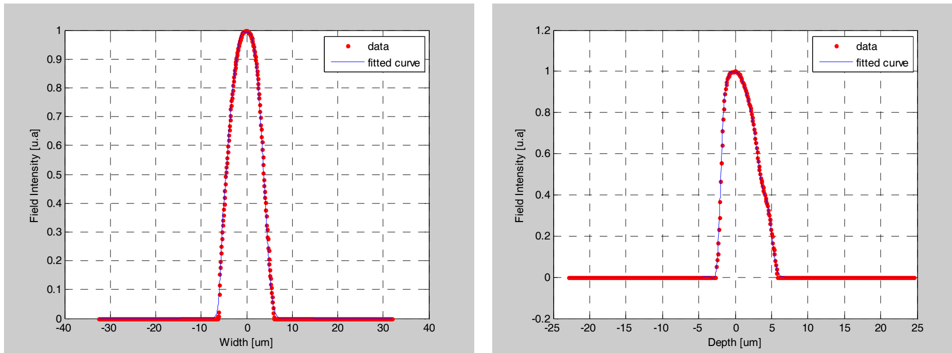
Figs. 8 a), b). The refractive-index difference profile in: width and b) depth for an 7.5 μm width and 52 mm long X-cut Er^{3+}:Ti:$LiNbO_3$ optical waveguide.



a) b)

Figs. 9 a), b). a) The width and b) the depth mode profiles of the measured near-field intensity for an 5 μm width and 54 mm length X-cut Er^{3+}:Ti:$LiNbO_3$ optical waveguide by using a CCD camera.

Also, using a CCD camera we measured the width and the depth mode profiles of the near-field for several Er^{3+}:Ti:$LiNbO_3$ and Ti:$LiNbO_3$ optical waveguides. In the case of an 5 μm width and 54 mm length X-cut Er^{3+}:Ti:$LiNbO_3$ optical waveguide the width and the depth mode profiles of the near-field intensity are presented in Figs. 9 a), b) while in Fig. 10 the measured and the processed curves using Gaussian functions (Eq. (4)) of the same waveguide are presented.



a) b)

Figs. 10 a), b). a) The width and b) the depth mode profiles of the measured near-field intensity (dotted) like in Figs. 9 and processed (continuous) curves using Gaussian functions of an 5 μm width and 54 mm length X-cut Er^{3+}:Ti:$LiNbO_3$ optical waveguide.

Using Eq. (5) we evaluated the coupling loss between the optical fibre and Ti:$LiNbO_3$ and Er^{3+}:Ti:$LiNbO_3$ optical waveguides having several widths, the results being presented in Table 1 and Table 2, respectively.

As can be seen from these tables the coupling loss coefficients present a minimum, therefore a maximum energy transfer from fibre to waveguide, for the following values of the waveguide widths: 5.5 μm in the case of Ti:$LiNbO_3$ optical waveguides and 7.5 μm in the case of Er^{3+}:Ti:$LiNbO_3$ optical waveguides. The obtained results are in good agreement with other results published in the literature [1].

Table 1

Coupling loss between the optical fibre and Ti:$LiNbO_3$ optical waveguides

Ti:$LiNbO_3$ waveguide width (μm)	w_3 (μm)	w_1 (μm)	w_2 (μm)	η
5	7.342	3.068	7.954	0.826
5.5	7.691	2.613	8.068	0.773
6	7.807	2.841	7.386	0.809
6.5	7.400	2.727	6.932	0.825
7	7.633	3.409	6.932	0.871
7.5	7.924	4.091	7.272	0.888
8	7.691	3.863	6.250	0.908
9	7.574	3.863	5.795	0.918

Table 2

Coupling loss between the optical fibre and Er^{3+}:Ti:LiNbO$_3$ optical waveguides

Er^{3+}:Ti:LiNbO$_3$ waveguide width (μm)	w_3 (μm)	w_1 (μm)	w_2 (μm)	η
5	5.710	4.090	3.523	0.966
5.5	7.050	4.545	5.909	0.959
6	6.293	3.863	5.227	0.956
6.5	7.167	4.204	6.477	0.937
7	7.983	3.750	7.841	0.853
7.5	8.215	3.636	8.636	0.813
8	7.516	4.318	7.045	0.917

4. Conclusions

We report a theoretical and experimental analysis of the coupling between graded refractive-index optical fibres and also between optical fibres and Ti:LiNbO$_3$ and Er^{3+}:Ti:LiNbO$_3$, respectively optical waveguides for λ=1.55 μm using nondestructive methods. The coupling loss coefficients were evaluated between the above mentioned components by approximating the field profile with appropriate Gaussian functions.

The refractive-index profiles of the Er^{3+}:Ti:LiNbO$_3$ optical waveguides has been determined from near field intensity measurement using a standard optical fibre as receiver and also a CCD camera. Using the Helmholtz scalar equation and a deconvolution procedure we evaluated some parameters which characterize Er^{3+}:Ti:LiNbO$_3$ waveguides: the refractive-index difference and the penetration depth. The coupling loss coefficients present a minimum, therefore a maximum energy transfer from fibre to waveguide, for the following values of the waveguide widths: 5.5 μm in the case of Ti:LiNbO$_3$ optical waveguides and 7.5 μm in the case of Er^{3+}:Ti:LiNbO$_3$ optical waveguides.

The obtained results can be used for the design of optical fibre sensors and optoelectronic integrated circuits.

REFERENCES

[1] *G. Fan, J. Ning, L. Shang, Q. Han, Z. Chen*, A novel opinion about the coupling loss between single-mode fibers and waveguides, Journal of Optoelectronics and Advanced Materials, **Vol. 8** (5), pp. 1912-1914, 2006.

[2] *N. N. Puscas, D. M. Grobnic, I. M. Popescu, M. Guidi, D. Scarano, G. Perrone, and I. Montrosset,* Characterization of the Er^{3+}-Doped Ti:$LiNbO_3$ Waveguides: Losses, Absorption Spectra and Near Field Measurements, Optical Engineering, **35** (5), pp. 1311-1318, 1996.

[3] *S. Ghinoiu, N. N. Puscas*, Measurement and evaluation of attenuation and refractive-index profile of optical fibers, Scientific Bulletin Polytechnic University Bucharest, Series A: Applied Mathematics and Physics, **Vol. 67**, No. 2, p. 17-24, 2005.

[4] J. *Helms, J. Schmidtchen, B. Schuppert, and K. Peterman*, Journal of Lightwave Tehnology LT, **8** (5), pp. 625-634, 1990.

[5] *H. C. Rainsch*, Smoothing by spline function, Numerische Mathematik, **16**, pp. 451-454, 1971.