Dimensions and Refractive Index Estimates of Deeply Buried Optical Waveguides in Lithium Fluoride

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Abstract— **A recursive procedure is applied to the measured near-field profiles of buried optical waveguides recorded in a lithium fluoride (LiF) crystal by femtosecond laser pulses in order to estimate the core dimensions and the refractive index increase. Albeit the waveguides transversal section geometry is quite complex it is possible to obtain the horizontal and vertical widths and the average refractive index maximum increase assuming a simplified rectangular transversal section in the simulation. The procedure is validated by comparing the simulated results with the experimental near-field profiles and the maximum refractive index values of two commercial optical fibers. Typical dimensions of ~(8x10)μm^2 and refractive index changes of ~(2-10)x10^{-4} were obtained for the LiF waveguides at several wavelengths.**

Index Terms— Refractive Index Increase, Core Dimension, Optical Waveguide, Lithium Fluoride, Femtosecond Laser.

I. INTRODUCTION

The dimensions and refractive index (RI) of the core are important parameters for optical waveguides characterization. These two main attributes and the wavelength behavior permit to specify the light acceptance into the waveguide (numerical aperture), the propagation condition, dispersion relation, electromagnetic profile and cutoff frequency of a supported mode, as well as the coupling coefficient to other waveguides. All of these parameters can be controlled by changing the core dimensions, the core refractive index or both [1].

The increase (Δn) in the spatial RI profile and the waveguide core dimensions can be estimated by different techniques, such as reflectivity method [2], scattering pattern [3], surface plasmon resonance [4], prism coupling [5, 6], surface topography [7], refraction method and Δn estimate from near field profile (NFP) [8, 9]. An inversion of the scalar wave equation to estimate the dimensions and the RI profile of the waveguide is possible with good signal noise ratio NFP [10].

The experimental requirements associated to the mentioned techniques turn difficult their application to analyze the RI profile and core dimensions of deep buried optical waveguides recorded by high intensity pulsed laser beams. This recording technique consists of focusing a laser beam in a

sample that is displaced perpendicular or longitudinal with respect to the laser propagation direction [11, 12]. The focused laser spot induces modifications of the sample structure resulting in RI changes. The RI profile recorded by this technique usually does not show a regular transverse shape [13, 14].

Recently, the writing of fs induced waveguides in Lithium Fluoride and several of their characteristics were reported [15, 16], the observed transversal cross section is also not regular, as can be seen in Fig. 1, which shows fluorescence confocal laser microscopy images of the transverse plane from (a) the side face and (b to d) from the bulk of a lithium fluoride crystal, where several optical waveguides were recorded by a femtosecond pulsed laser. The visible fluorescence is due to the local formation of laser-active aggregate color-centers in the LiF matrix [15, 16]. Figure 1(e) shows the NFP measured from one waveguide when using an ASE source, with central wavelength at 1550 nm, to launch light into the waveguide.
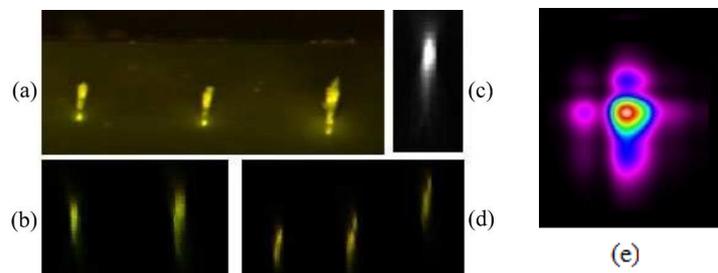
Fig. 1. Core transverse section of optically recorded color-center waveguides in a LiF crystal as seen by fluorescence confocal laser microscopy: (a) side face, (b-d) inside the crystal and (e) the NFP from waveguide #4, @1550 nm,

In this manuscript we detail the recursive procedure used to estimate the average Δn and transverse dimensions of that optical waveguides, deeply recorded by intense laser pulses in an optically transparent material such as LiF. The approach uses a non destructive technique to measure the NFP. Assuming a rectangular core with step refractive index profiles, a recursive procedure is applied to the experimental data. The approach is validated on two commercial optical fibers, comparing the obtained results with their known parameters. Subsequently the procedure is used to estimate the average Δn and the transverse dimensions of optical waveguides recorded ~160 µm deep from the top polished surface in a LiF crystal, at several wavelengths.

II. MATERIALS AND METHODS

A. Numerical Modeling

The proposed procedure uses (i) the NFP measured at a specific wavelength (635 nm, the measured data is treated with 1 Hz low-pass filter in order to reduce the numerical error in the second derivatives calculation [8]) to estimate the maximum Δn values in the horizontal and vertical directions, $\Delta n_{\mathrm{H}}(x, y_0)$ and $\Delta n_{\mathrm{V}}(x_0, y)$, respectively. The estimation uses an inversion of the scalar wave equation obtained from [8]

$$\nabla_T^2 \psi(x,y) + [k_o^2 n^2(x,y) - \beta^2]\psi(x,y) = 0 \tag{1}$$

where ∇_T^2 is the Laplacian operator in the plane transversal to the propagation direction, $\psi(x,y)$ is the field function amplitude, k_o the vacuum wave number, n the refractive index of the medium and β the propagation constant. Considering a small refractive index increase, Δn, and disregarding the square term, $\Delta n^2(x,y)$, it is possible rewrite equation (1) as[8]

$$\Delta n(x,y) = \frac{\beta^2}{k_o^2 2n_B} - \frac{n_B}{2} - \frac{\nabla_T^2 \sqrt{I(x,y)}}{k_o^2 2n_B \sqrt{I(x,y)}} \tag{2}$$

where $I(x,y)$ is the near field intensity measured experimentally and n_B the refractive index of the surrounding medium, in this case the LiF bulk value at the selected wavelength. (ii) The estimated maximum Δn_H and Δn_V are used to simulate the NFP of an optical waveguide at the same wavelength of the light source used to obtain the experimental NFP. Due the unknown core shape of the waveguides, the NFP simulation considers a simplified rectangular core transverse section and TE polarization. The propagation constant is obtained from effective index method and the spatial field distribution from Marcatili's Method [1, 17]. The waveguide transverse section dimensions, H and V, related to the horizontal and vertical directions, respectively, are adjusted to achieve the best fit between experimental and simulated NFP. The results consist of a set of transverse section dimensions as function of the RI estimate for the horizontal and vertical directions. (iii) Finally, in order to corroborate the estimate values of RI and core dimensions, the procedure is applied using NFP measured with light sources at other two wavelengths, 460 nm and 1550 nm, as well at 635nm. The values of Δn, *H* and *V* are adjusted to achieve best fitted experimental and simulated NFP for the set of three different wavelengths. The final data consist of a set of Δn values, each one related to a considered wavelength and just one couple of dimensions *H* and *V* for each waveguide. The code was implemented in MATLAB.

B. Numerical Test on Optical Fibers

The NFP simulation procedure is applied to the analysis of two commercial optical fibers (FSSN-3224-SM @ 632.8 nm and COA-SMMF-SM @ 1550 nm. The proposed approach was tested using the maximum Δn values estimated from the measured NFP for both optical fibers. The results were also compared with the step-index profile provided by the manufacturers. The NFP measurements were performed by using a semiconductor laser at 635 nm and a broad C-band source.

As an example, Fig. 2a shows the Δn_H estimated from the measured NFP together with that value provided by the manufacturer for the single mode fiber at 1550 nm. Fig. 2b shows the experimental NFP compared with those calculated by using the Δn maximum values reported in Fig. 2a and the Δn reported by the manufacturer.
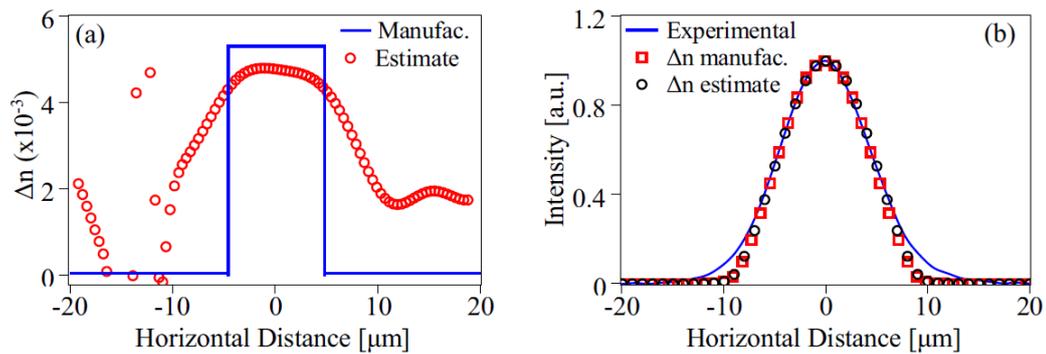
Fig. 2. (a) Δn spatial profiles provided by the manufacturer and the estimated one derived from the NFP measured at 1550nm and (b) the experimental and simulated NFP using the RI provided by manufacturer and the maximum value of the estimated Δn for the COA-SMMF-SM sample.

In Fig. 2b the central region of the simulated intensity profile (from its maximum to about 35 % of it) agrees well with the measured NFP for both wavelengths, the absolute mean errors are less than 1 % and than 2 % for the single mode optical fibers at 632.8 nm and 1550 nm, respectively. The tails show differences attributed to the transverse core geometry, circular for the commercial optical fibers and rectangular in the simulations. Table I shows the values of the full width at half maximum of NFP as derived from measurements and from the simulations for the two optical fibers at both wavelengths, using the Δn values provided by the manufacturer and those estimated by the NFP. In both case, the differences are consistent with the uncertainty of the used NFP measure system (~5 %) and agree with the values provided by the optical fibers manufacturers: 4.0 ± 0.5 μm and 10.5 ± 0.8 μm for single mode optical fibers at 632.8 nm and 1550 nm, respectively.

TABLE I. OPTICAL FIBERS MODAL FIELD DIAMETER, FWHM [μm], AT TWO WAVELENGTHS.

Optical Fiber	Direction	Experimental	Calculated	
			Δn Manufacturers	Δn Estimated
SM@632.8nm	H	4.05	4.01	4.06
	V	4.11	4.01	4.07
SM@1550nm	H	10.45	10.16	10.37
	V	10.56	10.14	10.34

C. Experimental Details

We analyzed color-center optical waveguides recorded in a LiF crystal, which has a RI of 1.39599, 1.39123 and 1.38275 at the wavelengths 457.9 nm, 635 nm and 1550 nm, respectively [18]. The crystal was directly irradiated with a focused femtosecond laser beam using a 20X microscope objective. The laser has 1 kHz repetition rate and emission band centered at 800 nm. The optical waveguides were recorded at depths of ~160 μm below the polished crystal top surface. The NFP was measured launching different light sources in the waveguides by a 10X microscope objective. At the end of the waveguide a similar objective collimated the emerging light into Thorlabs Beam Profiler

(models BP104UV and BP104IR, depending on the used wavelength). The microscope objectives and the LiF crystal were assembled on translation stages Newport ULTRAlign 561 series to achieve the optical alignment. The LiF crystal is hard and it is difficult to properly polish or cleave its side facets. This implies that mechanical damages generated by the focalized laser beam on the entrance and exit sides during the waveguides recording process could not be fully eliminated. Methods that require high quality of the NFP measure can have limitations under such conditions [8, 9].

III. RESULTS AND DISCUSSION

Using the described approach the core dimensions and the corresponding Δn are adjusted to match the experimental NFP at each of the used wavelengths. Table II shows the recording parameters of the LiF waveguides (laser energy and sample translation velocity), the calculated values of the core dimensions and Δn increase, from the best fitted simulated NFP.

TABLE II. RECORDING PARAMETERS, CORE DIMENSIONS AND REFRACTIVE INDEX CHANGE

VALUES ESTIMATED AT THREE WAVELENGTHS FOR SEVERAL LiF WAVEGUIDES.

Guide#	E [μJ]	v [μm/s]	Core dimensions		Δn(x10^{-4})		
			H [μm]	V [μm]	460 nm	635nm	1550nm
4	2	241	8.1	10.9	8	5.9	3.0
5	5	241	8.2	10.0	9	3.8	2.2
6	5	191	8.3	9.6	8	4.0	2.3
7	2	191	8.3	10.2	10	6.1	2.8

Fig. 3(a, c) shows the experimental NFP as measured at 635 nm and after numerical processing with a 1 Hz low pass filter, I and I_f, respectively, for the horizontal (Fig. 3a) and vertical (Fig. 3c) directions. From these plots it is possible to see that the filtering process influences only the noise on the Δn estimate, without distorting its main features, as shown in Fig. 3(b) and (d). According with these values, the experimental and simulated NFP for the waveguide #4 on horizontal and vertical directions are shown in Fig. 4(a) and (b), respectively. The difference between the simulated and measured NFP intensity profiles outside the central region can be attributed to several factors, including scattering of light at damage regions caused by laser ablation at the waveguide exits, multi modal propagation, leaky modes and interference patterns generated by reflections. Disregarding these side regions, the measured intensity profiles agree well with the simulated NFP.

Table III summarizes the values of the full width at half maximum of the experimental and simulated NFP corresponding to the dimensions and refractive index differences given in Table II for several wavelengths.
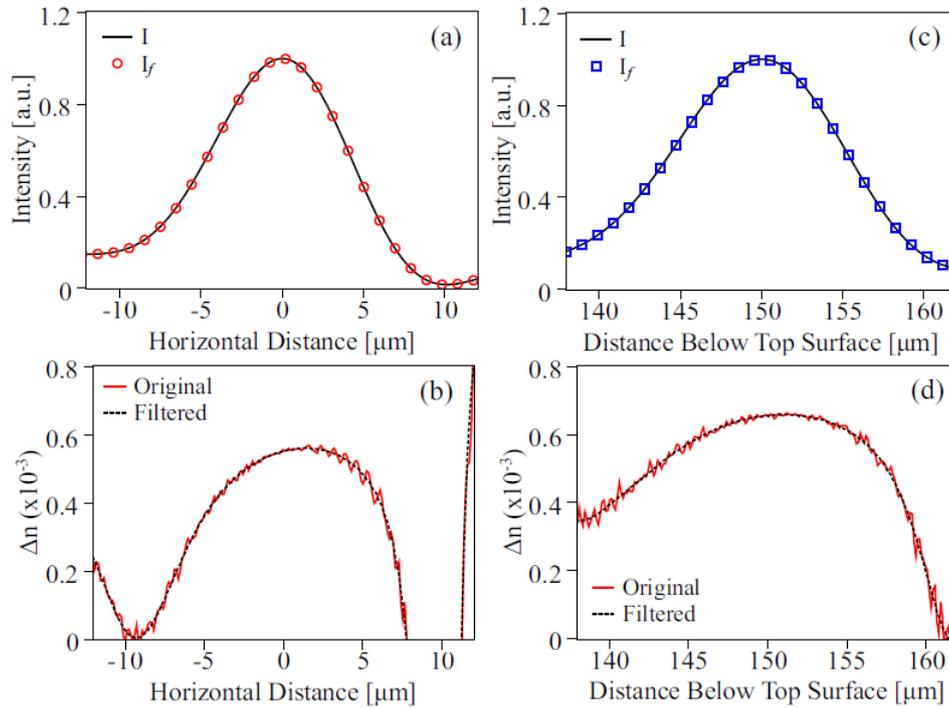
Fig. 3. Measured, *I*, and filtered, I_f , experimental NFP (a,c) and Δn estimate (b,d)
on horizontal (a-b) and vertical (c-d) directions of waveguide #4 at 635 nm.
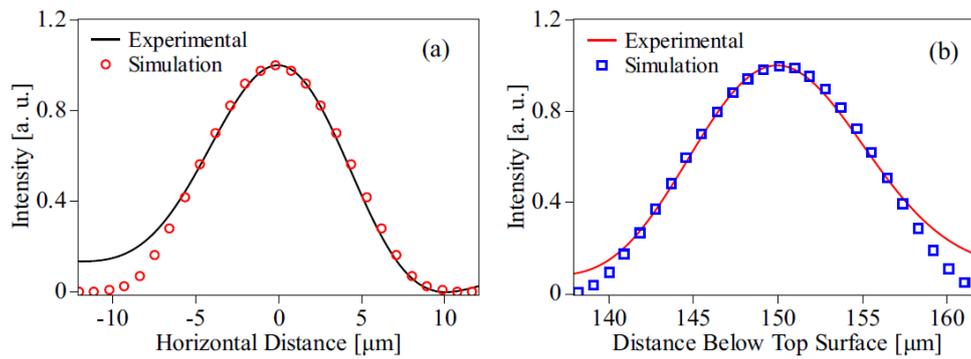
Fig. 4. Experimental and simulated NFP of waveguide #4 at 635 nm, for (a) horizontal and (b) vertical directions.

TABLE III EXPERIMENTAL AND CALCULATED FWHM OF SEVERAL LiF WAVEGUIDES AT THREE WAVELENGTHS.

| Guide# | | FWHM [μm] at wavelengths | | | | | |
| | | 460nm | | 635nm | | 1550 nm | |
		H	*V*	*H*	*V*	*H*	*V*
4	Exp.	9.3	12.1	9.7	12.6	16.8	15.5
	Sim.	9.0	11.9	9.8	12.5	14.5	17.0
5	Exp.	9.5	10.1	10.6	12.8	18.7	14.9
	Sim.	9.1	10.9	10.3	12.1	16.4	17.9
6	Exp.	9.5	9.8	10.6	12.5	17.7	17.0
	Sim.	9.2	10.5	10.4	12.0	15.7	17.1
7	Exp.	9.6	11.3	9.8	12.0	16.7	16.7
	Sim.	9.2	11.1	9.9	11.8	15.0	16.6

At 460 nm and 635 nm the differences in the values of core dimensions directly derived from NFP and those calculated on the basis of the Δn values of Table II are less than 8 %. The greater mismatch at 1550 nm can be ascribed to effects of the broadband light source used to measure the profile, with respect to the single line wavelength used for the simulation. In this case, the experimental NFP measures consist of a modal profile composition as a function of the wavelength.

IV. CONCLUSIONS

The results obtained with the proposed approach, together with those obtained in the numerical test performed on commercial optical fibers, show the possibility to estimate the core dimensions and the average increase of the refractive index of LiF optical waveguides without the need of knowing details about the core shape and Δn profile. Assuming a simplified rectangular transversal section, the Δn increase and the transversal dimensions were estimated by a recursive procedure used to compare the experimental and simulated NFP of the waveguides at several wavelengths. The recursive procedure permits to estimate these parameters from measured data with simple numerical treatments.

The estimated Δn values obtained for optical waveguides recorded by fs laser pulses in LiF are in order of $(2 - 10)\text{x}10^{-4}$, at wavelengths in the visible to near-infrared spectral range and the best fitted core dimensions are $\sim(8\text{x}10)\ \mu m^2$. The obtained results also support the possibility of recording low index contrast buried optical waveguides in lithium fluoride crystal by femtosecond laser irradiation, having single to few modes of propagation.

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