AN FDTD ASSESMENT OF TRANSVERSE INTERFEROMETRIC MEASUREMENTS OF INTEGRATED OPTICAL WAVEGUIDES

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Abstract

The FDTD technique is proposed as a tool to assess the index profile characterisation of dielectric waveguides via the Transverse Interferometric Method. Different index steps and profile shapes are tested and results commented.

I. INTRODUCTION

The knowledge of the refractive index profile is fundamental to determine the propagation properties of optical waveguides (single mode transmission band, confinement factor, etc.). Dielectric waveguides are fabricated using different techniques (ion exchange, proton exchange, with or without annealing, etc.) and, depending on the involved technological processes, the distribution of the index profile can be suitably tuned. Usually, the process supplies a defined shape of the index distribution, but the values of some parameters (depth of the modifications introduced in the refractive index of the substrate, maximum value of the index contrast, etc.) should be accurately measured.

The Transverse Interferometric Method (TIM) is a well known non destructive technique [1] which allows to retrieve these parameters from the phase delay induced on a plane wave illuminating the transverse section of an investigated waveguide. The measurement of this phase delay is evaluated by the fringe shifts of an interference pattern obtained inserting the sample in one arm of an interferometer. The index profile, is then computed from this phase delay by means of an inversion technique based on ray optics approximation. This technique assumes that optical rays follow almost straight paths within the waveguide core. Moreover, some hypothesis on the shape of the index profile are also needed in the calculations. Therefore, to asses the accuracy of the measure, it is very important to evaluate the errors determined by possible failures of both these assumptions.

The Finite-Difference Time-Domain (FDTD) technique, allowing to compute without any approximation the wavefront distortion induced by a given index distribution on an impinging field, provides basically the same results of a TIM measurement. Using a ray optics based inversion model [1], one can then retrieve the index profile from the FDTD results. Therefore, comparing this computed profile with the original one used for the simulation, the accuracy of the considered inversion technique when a TIM measurement is performed can be determined. In this work, two different situations are investigated. The former refers to measurements on high index contrast waveguides, where the optical rays strongly deviate from the supposed rectilinear path. The latter, on the contrary, refers to situations where the known index profile is not correctly characterised. Results are illustrated and commented, thus giving an effective insight on the sensitivity of the TIM method to the formulated assumptions.

II. THE TRANSVERSE INTERFEROMETRIC METHOD

In a TIM measurement, as anticipated in the previous section, the sample to be investigated is placed in one arm of an interferometer (Mach-Zender or Michelson type). A plane wave passing through the two arms suffers different delays, according to the different optical paths. Therefore, interference between the two wavefronts results in fringes. When the plane wave propagates in a homogeneous dielectric, as for example in the substrate region, the fringe pattern is regularly distributed on the interference plane and fringes are parallel to each other. On the contrary, the propagation in the core region introduces a distortion in the wavefront, which results in fringe shifts. The index distribution of the investigated sample can be evaluated processing the results of the measurement of this fringe displacement. When the index profile is not axially symmetric, as in the case of the waveguide represented in Fig. 1, and the illuminating uniform plane wave propagates along the *x* or the *y* axes of the reference coordinate system respectively, if one can assume that no diffraction takes place in the core, the fringe shifts along the *y* and *x* directions are given by [1]:

$$S(\delta) = \frac{D}{\lambda}\int_{-\infty}^{0}\Delta n(x,\delta)\,dx \quad (1) \qquad\qquad S'(\gamma) = \frac{D}{\lambda}\int_{-\infty}^{+\infty}\Delta n(\gamma,y)\,dy \quad (2)$$

where D is the distance between two adjacent undistorted fringes, λ is the free space wavelength of the optical source, δ is the coordinate along the *y* direction, γ is the coordinate along the *x* direction and $\Delta n(x,y)$ is the refractive index change of the core with respect to the substrate. Note that, due to the choice of the reference system, the upper limit of the first integral must be set to 0, while the lower limit can be set to infinity, as Δn=0 outside the core. The hypothesis that the wavefront propagates rectilinearly through the index varying medium reasonably holds in small samples and for index profiles with weak variations Δn between the core and the substrate.

To determine the index profile distribution, one must then solve the integral equations (1) and (2). For an axial symmetric step index optical fibre, these equations are of the Abel's integral type and can be integrated with some mathematics [1]. For dielectric waveguides such as those of Fig. 1, the inversion of the integrals in (1) and (2) requires also the knowledge of the shape of the index profile. This distribution can be expressed, as usual, in the form:

$$n(x,y) = n_b + \Delta n_{max}\, f(x)g(y) \qquad (3)$$

where n_b is the constant index of the substrate, $f(x)$ and $g(y)$ are normalised functions of the two coordinates separately and Δn_{max} is the maximum variation of the refraction index of the waveguide respect to n_b.

Once both $S(\delta)$ and $S'(\gamma)$ have been measured, considering the equations (1), (2) and (3) one can obtain:

$$\Delta n_{max}\, f(\gamma)g(\delta) = \frac{V(\delta)H(\gamma)}{\int_{0}^{\infty}V(y)\,dy} \quad (4) \qquad \text{where} \quad V(\delta) = \frac{\lambda}{D}S(\delta) \quad H(\gamma) = \frac{\lambda}{2D}S'(\gamma)$$

which supplies the desired $n(x,y)$ function.

III. RESULTS

To analyse the results of a TIM measure on a diffused graded index dielectric waveguide, a 2D FDTD simulator in the *total field/scattered field* formulation [2] has been set-up. The waveguide has been considered inside the total field region and illuminated by a TE polarised plane wave (Ez, Hx and Hy) propagating from the CD plane along the *x* direction (see Fig. 1).

For all the performed FDTD simulations reported here, a λ = 1.3 μm exciting plane wave and a square computational domain 30 μm wide with a $\Delta x = \Delta y = 0.05$ μm lattice have been considered. This guarantees the required accuracy in the representation of both the electromagnetic (e.m.) field and the index profile distribution. To absorb the e.m. field on the boundary of the *scattered field* region, Perfectly Matching Layers absorbing boundary conditions have been used [3].

The phase delay induced by the non-homogeneous dielectric core on the propagating plane wave has been obtained comparing the outgoing field in the section EE with that corresponding to a propagation of the same impinging field in a n_b constant index dielectric medium. In the simulations, the normalised functions *f(x)* and *g(y)* are respectively assumed as:

$$f(x) = e^{-\left(\frac{x}{D_x}\right)^2} \qquad g(y) = 0.5\left[erf\left(\frac{y + W_y/2}{D_y}\right) - erf\left(\frac{y - W_y/2}{D_y}\right)\right] \qquad (5)$$

where D_x and D_y are the diffusion depths and W_y is the diffusion width. As a consequence, one can also set:

$$n(x) = f(x) \quad n(y) = \Delta n_{max}\, g(y) \qquad (6)$$

As the plane wave propagates along the *x* direction, an exponential function with a diffusion depth $D_x = 2$ μm has been considered as the known *n(x)* profile. For waveguides with $\Delta n_{max} = 0.015$ (weak index contrast), as illustrated in the upper plot of Fig. 2, where the *n(y)* profile used for the simulation and the computed one obtained by inversion of the integral equation (4) are compared, the simulated results reproduce the correct profile of the index distribution along the *y* direction. On the contrary, for $\Delta n_{max} = 0.493$ (deliberately very large index contrast) the hypothesis of rectilinear propagation of the impinging plane wave inside the non-homogeneous core fails, thus inducing a significant error in the computed *n(y)* even if Δn_{max} does not suffer of the same problem, and it is correctly determined. Note that only one half of this profile is plotted because of the symmetry of *n(y)*.

Once the effectiveness of the method has been tested for the weakly guiding structure with $\Delta n_{max} = 0.015$, the influence of the hypothesis formulated on both the *n(x)* profile and the D_x parameter on the final results have been evaluated. The situation of incorrect choice of the *n(x)* function has been examined first. Using the phase delay computed by FDTD on the section EE, the integral (4) has been inverted considering also an *erf* and an *erfc* profiles for *n(x)*. As one can see in Fig. 3, both of these profiles supply incorrect values of the Δn_{max} parameter. The effects on the final results of the parameter D_x have then been investigated. In this case, the correct exponential function for *n(x)* has been assumed, and both the correct value of D_x =2 μm and the incorrect one of D_x =1 μm have been used respectively in the integral inversions. As shown in Fig. 4, also in this case the computed profile strongly depends on the chosen values of the diffusion depth.

IV. CONCLUSIONS

In this work, the FDTD technique has been used to analyse how the hypothesis of a rectilinear ray propagation inside a non-homogeneous dielectric medium and on the shape of the index profile influence the measure of refractive index distribution via a TIM technique. Two situations have been independently examined, in order to have insights on the effectiveness of this method with respect to these two constraints. Results show that TIM is very sensitive, in the reconstruction of the transverse index profile parameters, to the knowledge of the longitudinal profile shape and diffusion depth. On the contrary, if the longitudinal profile is known, the index contrast can be obtained with good accuracy also for waveguide with large index steps.

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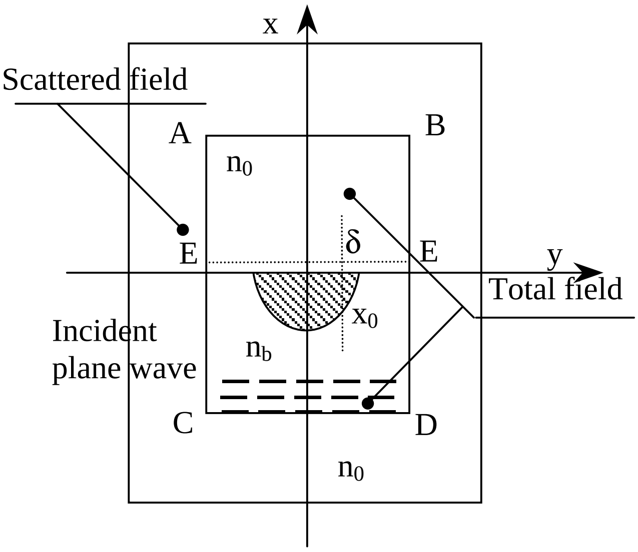

Fig. 1 Geometry of the simulated waveguide inside the FDTD computational domain with the total and scattered field regions.

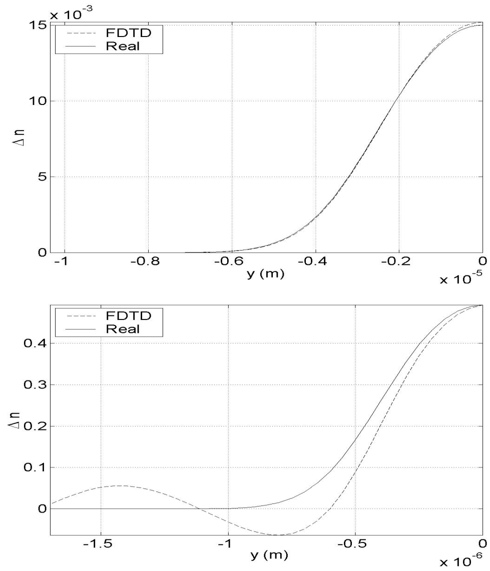

Fig. 2 Comparisons between the real and the estimated (FDTD) *n(y)* index profile. Upper picture $\Delta n_{max} = 0.015$; lower picture $\Delta n_{max} = 0.493$.

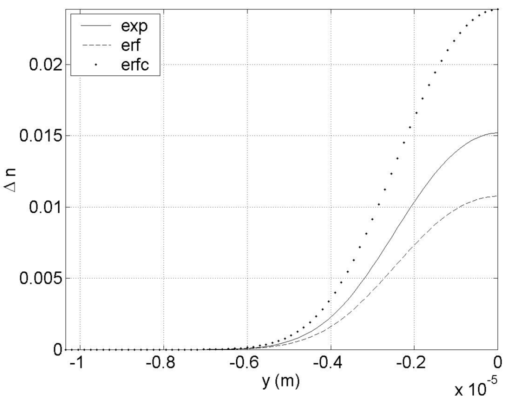

Fig. 3 Transverse index profile distributions *n(y)* computed by FDTD for different hypothesis on the *n(x)* function and the same $\Delta n_{max} = 0.015$.

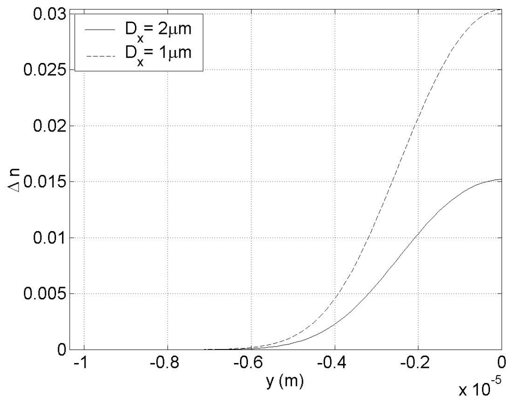

Fig. 4 Comparisons between the *n(y)* profiles computed by FDTD with the correct *n(x)* function and two different values of the diffusion depth parameter D_x.

References

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