Finite Difference Time Domain Method Analysis of Doped Photonic Crystal Fiber for Communication Systems

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Abstract— **the geometry effect of the structure is put in profile during the survey of an important criteria of these fibers namely the confinement loss. To optimize an optical fiber structure constituted with a doped core, the value of confinement loss must be as low as possible; a new structure is introduced in our analysis. It is a structure formed by a doped core surrounded by a cladding which is composed by a photonic air holes in silica. These holes have an elliptic shape which is present some angular orientation. The first air ring around the core is oriented in a way that reduces the confinement loss values. The introduction of liquid with various values of refractive index in the elliptic holes still reduces the values of the confinement loss. The study of such a structure leads us to the study of Maxwell's equations therefore a numerical method is required, we chose the Finite Difference Time Domain method (FDTD) with transparent boundary condition (TBC).**

Keywords--- Doped Photonic Crystal Fiber, confinement loss, Finite Difference Time Domain method (FDTD) , transparent boundary condition (TBC)

I. Introduction

Nowadays the need for high bit rate is increasing where the growth of research on component and techniques involved in the remote transmission.

The optical fiber is a component of broadband transmission despite these limitations caused by the chromatic dispersion and the modal dispersion. This shows that in order to increase the transmission rates is need to develop new fibers. The propagation characteristics of these fibers meet the requirements of increasingly stringent. The PCF fibers [1-2], can meet on this requirement because they have interesting properties in terms of unimodal character and chromatic dispersion that can be adjusted according to the parameters of the fiber.

In our study we focus on the solid core photonic crystal fiber. This is a two-dimensional photonic crystal that consists of an array of unit cells arranged periodically. Each unit cell is generally in triangular shape. To have a difference index Δn between the core and the cladding, the core can be doped [3]. The doped core of silica fiber is surrounded by a photonic cladding that is composed of air holes in silica; the refractive index average is lower than that of the core where there may be a slight difference Δ_n in index.

Several researchers have been working on [4-5] and even for the sensor system [6].

The parameters that can influence the optical properties of the fibers are the distance between the centers of two adjacent holes noted Λ (pitch) and the holes diameter d. These parameters define the d / Λ ratio corresponding to the proportion of air present in the fiber (filling factor). The number of rows or rings of holes used to form the microstructured cladding is one of the criteria to reduce losses guide [7], these fibers guide the light by total internal reflection [8].

Recently other researchers have the idea of introducing a liquid into a few holes around the core [9] [10] [11] [12].This technique proves to be interesting for the adjustment of some properties of the fibers as confinement loss and the chromatic dispersion.

II. THEORY

The guide of the light is made by total intern reflections; this light is in fact an electromagnetic wave to study its distribution within the structure we have to solve the Maxwell's equations. The condition which must be verified it is that the propagation constant β will be between the possible maximal constant of propagation mode in the region of the core and the constant of propagation of the mode of cladding [13] [14];with equivalent index of the cladding, which can be calculated by[15]

$$n_g = \frac{\iint n^2 |E|^2 \, ds}{\iint E^2 ds} - \frac{1}{k^2} \frac{\iint \left|\frac{dE}{dr}\right|^2 ds}{\iint E^2 ds} \qquad (1)$$

With E the electric field, n the index of silica or material filling the holes, s the surface of the unit cell, r is the distance to the center of the fiber

The evaluation of the electric field is performed by the Maxwell's equation

$$\overline{\nabla} \times \overline{\mathrm{H}} = jw\varepsilon \overline{E} \qquad (2)$$

The Finite Difference Time Domain method (FDTD) is a direct numerical solution of Maxwell's equations.

Our 2D structure will be in the XZ plane, This method is based on the spatial and temporal discretization of Maxwell's equations [16] [17]. The propagation is along Z. The Y-direction is assumed to be infinite. This assumption removes all the ∂/∂y derivatives from Maxwell's equations and splits them into two (TE and TM) independent sets of equations.

$$\min imum(\Delta x, \Delta y, \Delta z) \le \frac{\lambda_{\min}}{10 n_{\max}} \qquad (3)$$

$$\Delta t \le \frac{1}{v\sqrt{\frac{1}{(\Delta x)^2} + \frac{1}{(\Delta y)^2} + \frac{1}{(\Delta z)^2}}} \qquad (4)$$

ν represents the speed of the light in the dielectric

In the area calculation n_{max} represents the maximum value of refractive index.

And for 2D structure

$$\Delta t \le \frac{1}{v\sqrt{\frac{1}{(\Delta x)^2} + \frac{1}{(\Delta z)^2}}} \qquad (5)$$

The confinement of light in the core is possible for some modes. These modes are the solutions of Maxwell's equations. They represent an adaptation of the light to the constraints imposed by the guide. Each mode has its own velocity and an effective index

The confinement losses are calculated from the imaginary part of the complex effective index [18]

$$CL \ (dB/km) = \frac{2 \times \pi \times 8.686 \times 1000 \times \mathrm{Im}(n_{eff})}{\lambda} \qquad (6)$$

III. MODELING AND ANALYSIS

The confinement loss is one of the most important parameters of guidance since losses confinement should not change the intensity of the signal propagated along the fiber. Several researchers worked on this subject [7] [19] Studies have shown that confinement losses can be adjusted by the geometry of the fiber (pitch value Λ hole diameter d), the number of row (ring) [7] and by the introduction of liquid in a few holes which surround the core [11] [20].

Our structure is formed of a core surrounded by a cladding which is composed by a photonic air holes in silica, his average refractive index is lower than the core where it may have a slight difference in index Δn. The core is doped so that allows us to adjust the difference Δn; the number of row of air holes is 5 rows around the core.

The values of Λ and d are respectively 2.75 μm,2 μm and 2 μm ,2 μm, Δn= 0.02 Fig. 1.

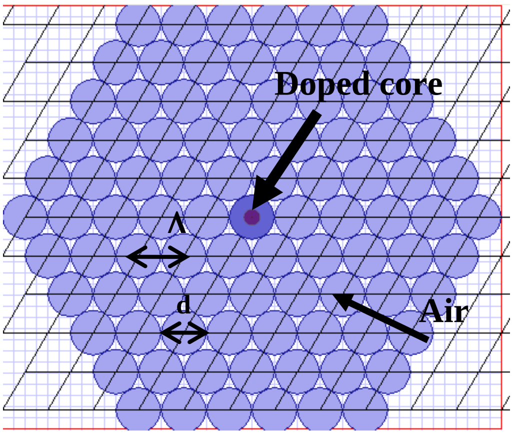

Fig.1 structural parameters of PCF

We have modelled solid core PCF using OPTIFDTD 8 software and to solve the electromagnetic problem we have used the Finite Difference Time Domain method (FDTD).

For the boundary condition there is many kind as Dirichlet, Neumann and TBC. To escape unwanted reflections from the boundaries we introduced transparent boundary condition (TBC).

First of all we are interested in the variation of the effective index as a function of wavelength.and The confinement losses for both cases d=2 μm ,Λ = 2.75 μm; d=2 μm , Λ = 2 μm Fig.2. and Fig.3.

we can notice that the effective index decreases (case of d=2 μm ,Λ = 2 μm) if we increase the wavelength value, whilst The confinement losses increases with increasing λ values and takes high values compared to the case where d = 2 μm, Λ = 2.75 μm.

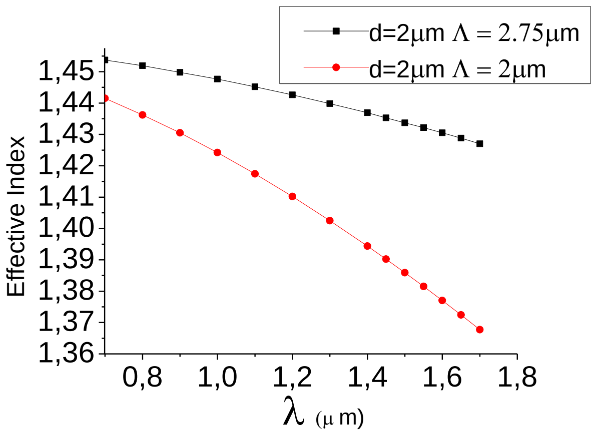

Fig.2 variation of effective index with the wavelength

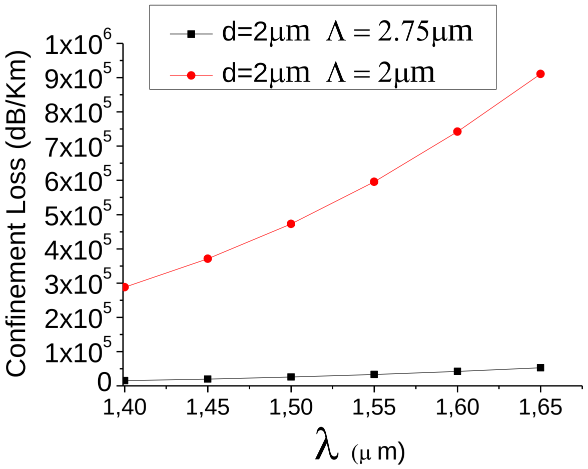

Fig.3 Variation of confinement loss with the wavelength

The structure in which d = 2μm, Λ = 2.75μm proves interesting Figure.4. Then we wanted to push still our analysis thus we were interested in the nature of the holes surrounding the core.

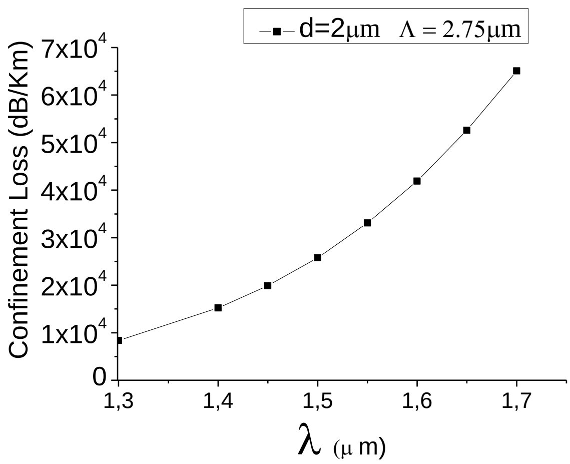

Fig.4 Variation of confinement loss with the wavelength case of d= 2μm and Λ= 2.75μm

Usually the cladding it's composed by photonic air holes in silica, in our work we are going to study a structure in which the cladding is composed of elliptical air holes Fig.5. and Fig.6. The ellipses have a major radius and a minor radius. Studied the structures have the following values R= 1μm, r =0.5 μm θ = 45° Λ = 2.75 μm ; R= 1 μm, r =0.75 μm θ = 45° Λ = 2.75 μm; R= 1 μm, r =0.5 μm θ = 45° Λ = 2 μm and R= 1 μm, r =0.75 μm θ = 45° Λ = 2 μm.

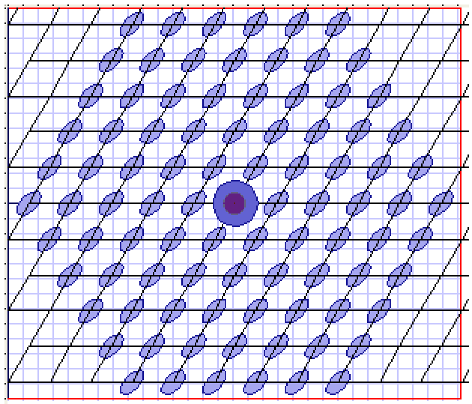

Fig.5 structural parameters of PCF with elliptical air holes

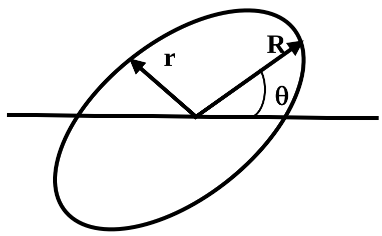

Fig.6.minor radius r, Major radius R, and orientation angle θ

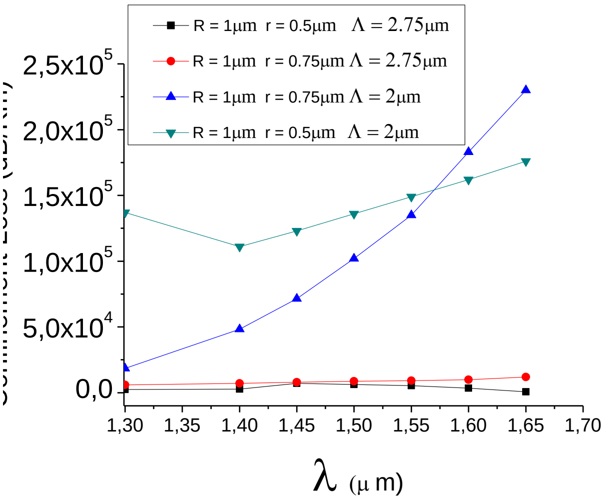

Fig.7 Variation of confinement loss with the wavelength case of PCF with elliptical air holes

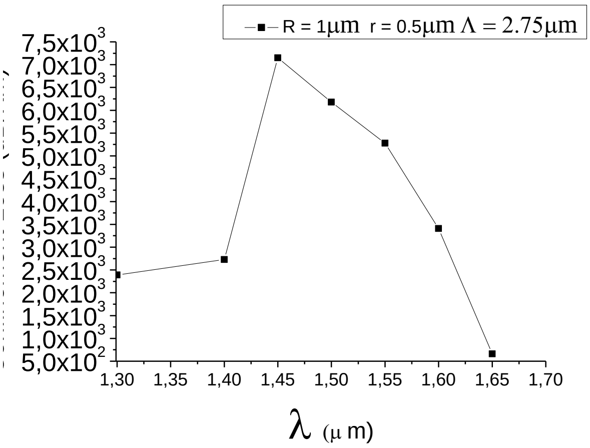

Fig.8 Variation of confinement loss with the wavelength case of R = 1µm r = 0.5µm Λ = 2.75µm

We can notice that the values of the confinement loss are more weaker for the structure R= 1 µm, r =0.5 µm $\theta = 45^o$ Λ = 2.75 µm let us compare with the other structures Fig.7. and Fig.8. Afterward we took this structure to study it in a more thorough way by varying the values of r; r varied from 0.5 µm to 0.95µm with R = 1 µm then R = 0.75 µm for the wavelength 1.55µm Fig.9.

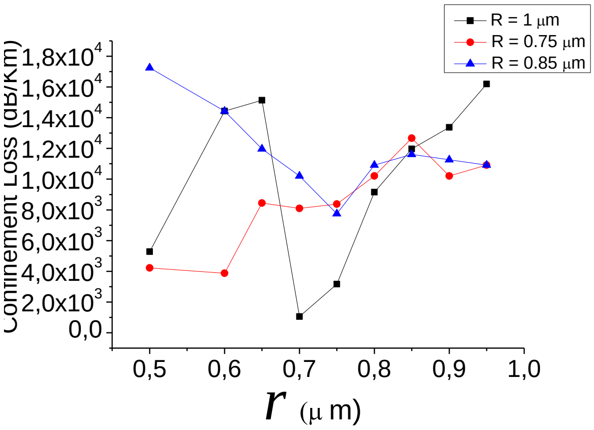

Fig.9 Variation of confinement loss with the variation of the minor radius r

We were able to see that for the values of R = 1µm, r= 0.7 µm $\theta = 45^o$ Λ = 2.75 µm the confinement loss is the lowest (1.055 10^{+3} dB / km) Fig.9. To push still the study we took a structure which presents a row around the core oriented 135 ° (Fig.10).

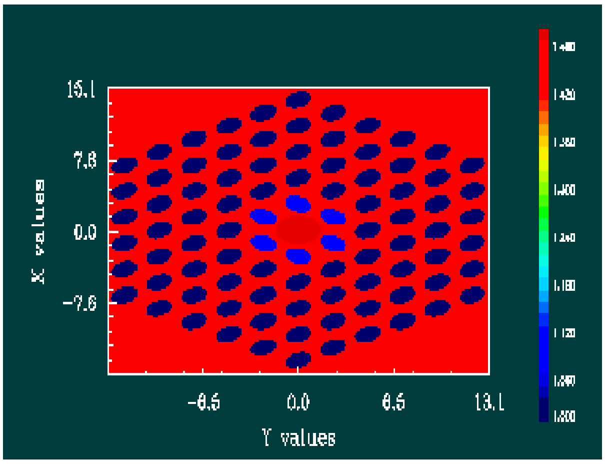

Fig.10 The distribution of the refractive index

Our simulation allowed us to see the distribution of the optical field within the fiber Fig.11.

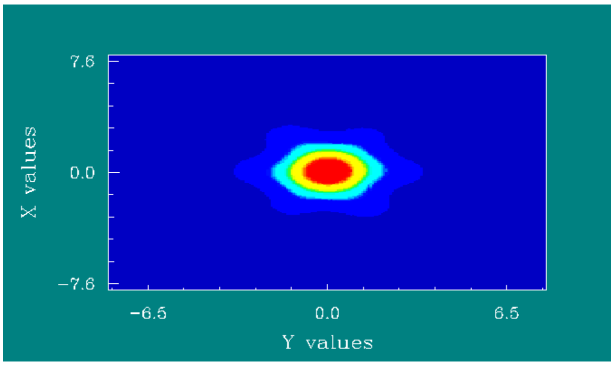

Fig.11.Optical filed Distribution

For Such a structure we noticed that the value of the confinement loss becomes lower it passed in the value of 2.81 10^{+3} dB/Km as the wavelength 1.55 but is still not enough weak in front of the value of the structure (R = 1μm, r= 0.7 μm,θ = 45°,Λ = 2.75 μm).

After we had the idea to introduce instead of the air into the first row we introduce some liquid with refractive index n_L [11] which varies and takes the values of 1.1; 1.2; 1.3. We can then see the Profile of the refractive index of the structure for one X cut either for one Y cut in the case of n_L=1.3 Fig.12. and Fig. 13.

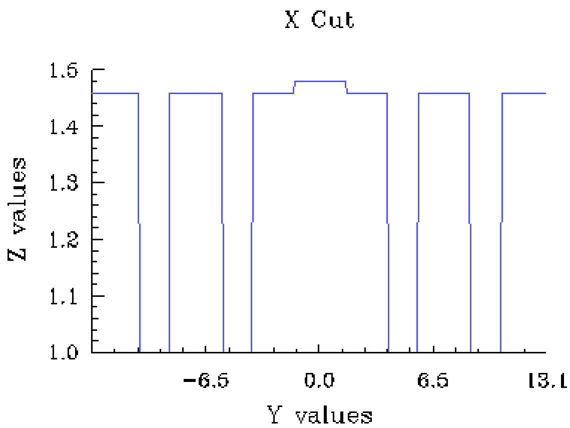

Fig.12. Profile of the refractive index of the structure (X cut) for n_L=1.3

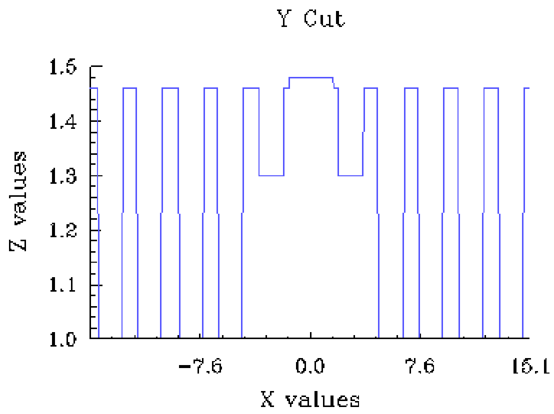

Fig.12. Profile of the refractive index of the structure (Y cut) for n_L=1.3

For the wavelength of 1.55 μm we were able to notice a weakening of the value of the confinement loss which passed from 2.81 10^{+3} dB/Km to 3.51 10^{+2} dB/Km, 2.81 10^{+2} dB/Km, 1.23 10^{+2} dB/Km respectively as the values of n_L 1.1; 1.2; 1.3 (Table 1)

Structure	n_{air}	n_L=1.1	n_L=1.2	n_L =1.3
Confinement Loss (dB/Km)	2.81 10^{+3}	3.51 10^{+2}	2.81 10^{+2}	1.23 10^{+2}

TABLE I: confinement loss value relatively to the holes index

IV. CONCLUSION

In this work we have studied the confinement loss which guides us in the choice of the photonic crystal parameters such of the holes diameter, the pitch and the forms of holes.

In this context we have studied a structure with elliptical air holes. The ellipse have a major radius and a minor radius, we studied the effect of the variation of this radius on the confinement loss value and the effect of the orientation angle. Our study showed that for five-ring and R= 1, r =0.7 θ = 45° Λ = 2,75 we have a value of confinement loss 1.055 10^{+3} dB/Km.

Afterwards we have studied a structure which present a row oriented with 135° around the core. We note that the value of the confinement loss decrease more than the case of R= 1μm, r =0.5 μm θ = 45° Λ = 2.75μm ; R= 1 μm, r =0.75 μm θ = 45° Λ = 2.75 μm; R= 1 μm, r =0.5 μm θ = 45° Λ = 2 μm and R= 1 μm, r =0.75 μm θ = 45° Λ = 2 μm but not sufficiently then the case of R = 1μm , r= 0.7 μm θ = 45° Λ = 2.75 μm. So To pushed yet our study, we introduced a liquid in the holes to varied their effective index and look at its effect on the confinement loss value. Indeed the introduce of a liquid with an effective index n_L= 1.3 decrease this value from 2.81 10^{+3} (dB/Km) to 1.23 10^{+2} (dB/Km).

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