The Effect of Pitch Size on The Dispersion Profile of Photonic Crystal Fiber

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Abstract:

The effect of pitch size on the dispersion profile of photonic crystal fibers (PCFs) is studied. (7) PCFs of one ring, one missing hole and hole diameter 0.4μm are investigated under the effect of the pitch size. The variation range of the pitches is (1.0 to 2.5)μm.

This paper shows that PCFs of pitches 1.7, 2.0, 2.3, and 2.5μm offer single mode operation from the visible to infrared region and the dispersion profile tend to be near flattened over a range of wavelength (0.95 to 1.45) μm. A blue shift in zero dispersion wavelengths is obtained due to the variation of the pitches. Additionally the results show a large decreasing in the confinement losses for the proposed PCF of Λ=2.5μm for fundamental mode. All the PCFs under study show lower confinement losses at the communication wavelength of 0.8μm, (Ti-Sapphire) laser compared with communication wavelength of 1.5μm.

Introduction:

A more recent class of optical fiber is photonic crystal fibers (PCFs) which is considered now *the-state-of–the–art*-of photonic crystal fiber because of their fine tunability of various guiding characteristics such as wide single mode wavelength range, unusual chromatic dispersion, the magnitude of the nonlinearity, and so on [1-3]. The first working example of PCFs was made by Knight *et al* in 1996 [2]. The basic structure of the PCF [4] is shown in Fig.1, transverse cross-sections of the fibers, with the main key parameters include the hole diameter d, and the spacing between hole centers (pitch size) Λ, in addition to the number of rings Nr, and the number of missing air holes MNr. The central region identities the location of the core, which may be either solid or air, its dimension is either one missing hole or more depending on the design and intended purpose [1,4,5]. The hole pattern is based on a simple triangular shape to form an over all hexagonal structure.

In comparison with conventional optical fibers (COFs), guided propagation of the electromagnetic field in the PCFs is achieved by the introduction air holes around a silica core, and acts as a cladding of the PCF[3]. The effective refractive index is considered as an average over the solid silica and the air holes it contains. Thus the cladding region has a lower average refractive index than the core and guides light similar to a step index optical fiber, which is shown in Fig.1, as an index profiles [4]. In either case, the region represents a defect in the structural pattern. If solid, the core radius extends to the inner edge of the first ring of holes, which means the air holes are typically arranged in a triangular lattice. In the center, an air hole is omitted creating a central high index defect serving as the fiber core. The guidance mechanism depends on the nature of the defects, the air hole arrangement and the number of the rings[4].

According to the guidance mechanism, PCF can be divided in to two categories*: first*, total internal reflection (TIR), (see Fig.1 guidance by TIR) where air holes surround a high index solid core, and *second*, photonic band gap (PBG), where the light is confined to a central air hole [5].

PCFs are found to exhibit remarkable properties which include single mode over wide range of wavelength [3, 4]. These properties are because the refractive index contrast between the core n_c and the refractive index of the surrounding region n_{cl} is large and the effective refractive index n_{eff} of the surrounding region is depends on wavelength.

Nevertheless, the main limitation of the photonic crystal fiber are currently the high losses induced, typically 1000 times higher than in conventional fiber [3].

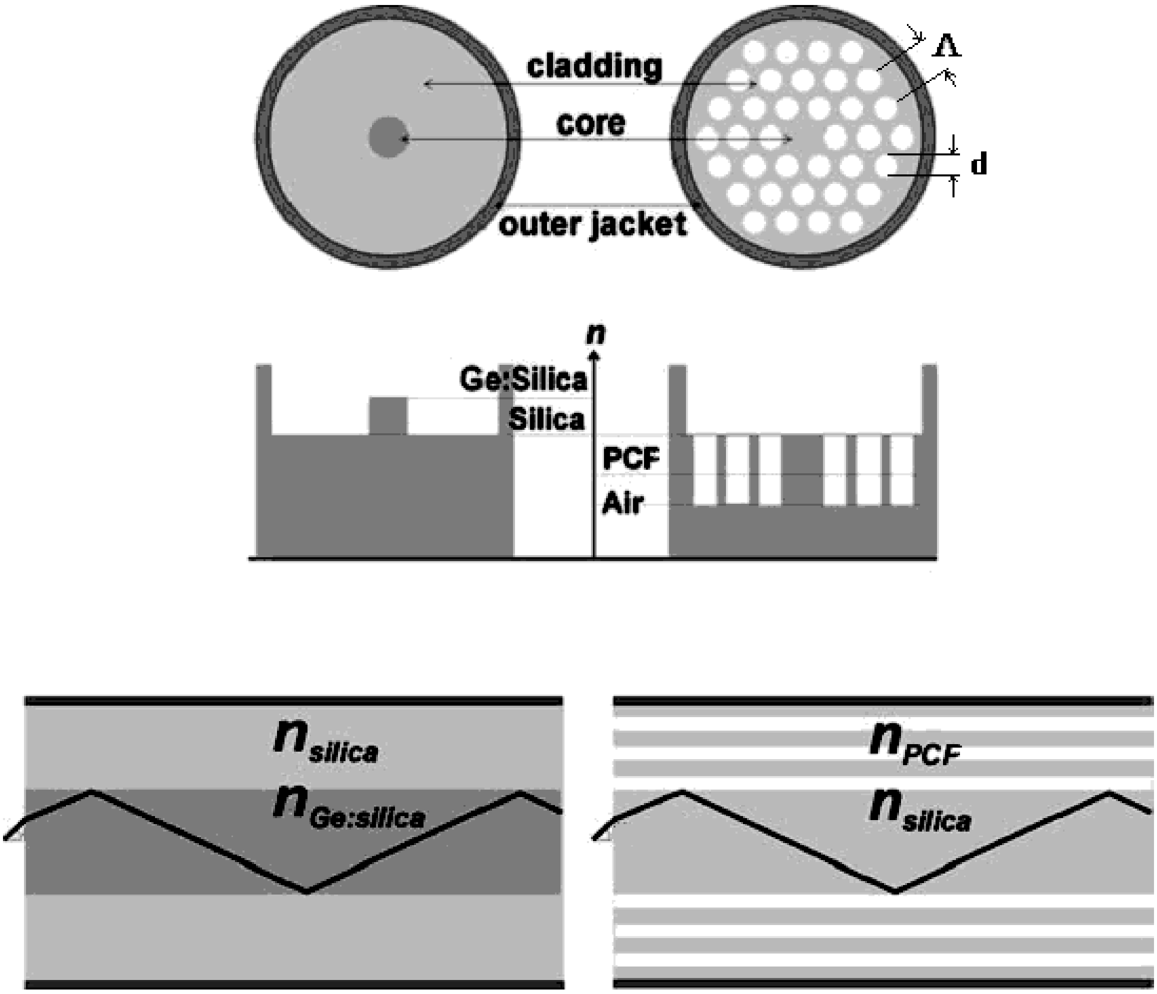

Fig.1. Schematic comparison between a step-index fiber and an index guiding PCF. Top: Transverse cross-sections of the fibers. Centre: Index profiles. Bottom: Guidance by TIR[4].

In studying the influence of some parameters of the PCF on the dispersion, Saitoh *et al*, [6] show that the zero dispersion wavelength for a PCFs of (d/Λ=0.7, Nr = 6, 8, 10 rings) can be pushed towards the visible region while a PCF still in single mode. While Wu *et al*. [7] designed a four ring PCF with different air holes, by optimizing only three geometrical parameters (d_1/Λ, d_2/Λ and Λ), they obtained nearly zero ultra flattened dispersion properties. Other PCFs studied by Ferrando *et al*. [8] and obtained the wavelength window for which the fiber dispersion remains between -1.0 and +1.0 $pskm^{-1}nm^{-1}$ interval over 543nm. The numerical results of Saitoh [9] show that it is possible to design; a four rings PCF with flattened dispersion from a wavelength 1.19 to 1.69μm (i.e interval over 500nm) and a five rings PCF with flattened dispersion from a wavelength 1.23 to 1.72μm (interval over 490nm).

The aim of this work is to demonstrate how the dispersion profile (for a PCF of one ring) may be tuned by the variation of pitch size for a given hole diameter along a range of wavelength.

This paper is organized as follows: In section 2, the explanation of the design principle and used software. In section 3 results and discussion. Finally conclusions and future work are given in section 4.

Design principle and used software:

In PCFs, the cladding region is usually formed by array of air holes in a regular triangular lattice; these holes are always packed in hexagonal form and regularly spaced with separation Λ [9]. The chromatic dispersion profile can be easily controlled by varying the values of any/or all of the following parameters; air hole diameter (d), pitch size (Λ), number of rings (Nr) and the number of missing hole (MNr). However, communications by short wavelength region, the guided mode is well confined into the core region and the dispersion curve is affected by inner air–hole rings while communications by long wavelength region, the effective area (A_{eff}) of the core is increased and the dispersion curve affected also by the outer rings i.e. particularly by hole to hole spacing (pitch size Λ). So the normalized frequency and the dispersion curve can be controlled to achieve a single mode and near flattened in wide range of wavelength for specific value of Λ.

To show how the dispersion curve is affected by the pitch size, we consider (7) PCFs each one of one ring (Nr=1), air hole diameter (d=0.4μm), one missing hole (MNr=1), accordingly the number of holes (NH) in a ring is different, (e.g. for N=1, NH=6 and for N=2, NH=12 and so on). So the change only in the pitch size (Λ_1 = 1.0 μm, Λ_2 = 1.3μm ,

Λ_3 = 1.5μm, Λ_4 = 1.7μm, Λ_5 = 2.0μm, Λ_6 = 2.3μm, and Λ_7 = 2.5μm.

Various groups have modeled PCFs by different numerical tools [6-12], for determining the PCF parameters. Multipole method [10-12] is on of them. Numerical simulation based on the multipole method, as applied to PCFs by White et al [10] and Kuhlmey et al**[**11] are used to calculate the effective index n_{eff} of the PCFs structure. The results of this paper are a combination of data from programs written by the authors (of this paper) and from the *CUDOS software*. This software is created and distributed by the University of Sydney **[**12**],** and the programs is an implementation of the multipole method which is very efficient for calculations on photonic crystal fiber with circular holes [12]. The accuracy of the programs has been assessed according to the recommended method **[**11**].** Furthermore multipole method yields both the real and the imaginary part of the mode propagation constant ($\beta=n_{eff}$ /k) where k is the wave number, the latter gives the confinement losses ($Im(n_{eff})=Im(\beta k)$ see section 3) associated with the finite extend of the PCFs set of confining holes. It can deal with two types of PCF; those with solid core surrounded with air holes, and those with cylindrical hole, of somewhat large radius, again surrounded by air holes [10]. Finally multipole method is thus well suited for calculations involving material dispersion.

Results and discussion:

We use the method described in the above section and calculated the real part of the refractive index for the proposed PCFs, for the fundamental mode. Fig.2 shows a wavelength dependence of the real part of the effective index $\Re(n_{eff})$ of the proposed PCFs, where the background index is assumed to be 1.46232648 for silica. This figure shows that, as the pitch size decreases the refractive index decreases, and the difference between the refractive index of the silica and the real refractive index of the PCF for the fundamental mode increases. Such a strong wavelength dependence of the $\Re(n_{eff})$, facilitates the unusual properties of the photonic crystal fiber.

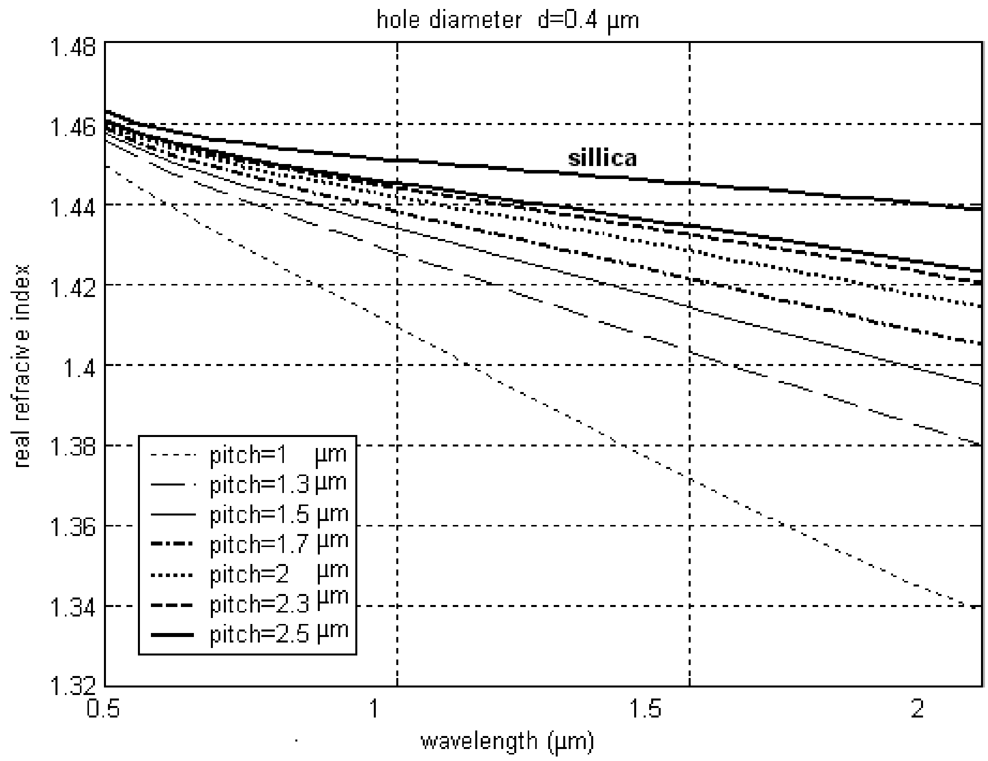

Fig.(2): Real refractive index for the proposed PCFs and silica.

The V parameter expression

PCFs can be well parameterized in terms of the V – parameter or the normalized frequency, by this parameter one can determine the number of confined modes which are exist in the core. In the context of PCF, Wong [13] and Mortensen et al [14] made a modification to that equation used in standard step index fiber.

$$V = ka\,(n_c^2 - n_{clad}^2)^{1/2} \qquad (1)$$

If n_{clad} is replaced by n_{eff} and a by Λ to get:

$$V = k\Lambda\,(n_c^2 - n_{eff}^2)^{1/2} \qquad (2)$$

here k, a, n_c, n_{clad}, Λ, and n_{eff}, are the wave number, core radius of the standard step index fiber, refractive index of the clad, pitch size, and the effective refractive index of the air hole array in PCF respectively [13, 15].

Fig.3 shows the curves for the V-number as a function of wavelength for a PCFs of pitches Λ=1, 1.3, 1.5, 1.7, 2.0, 2.3, and 2.5μm. The PCFs of pitches 1.7, 2.0, 2.3, and 2.5μm /or of the relative air hole size d/Λ <0.24 are seen to nearly constant level over a range of wavelength. And the single mode condition when $V \leq \pi$ as obtained by Mortensen *et al* [16].

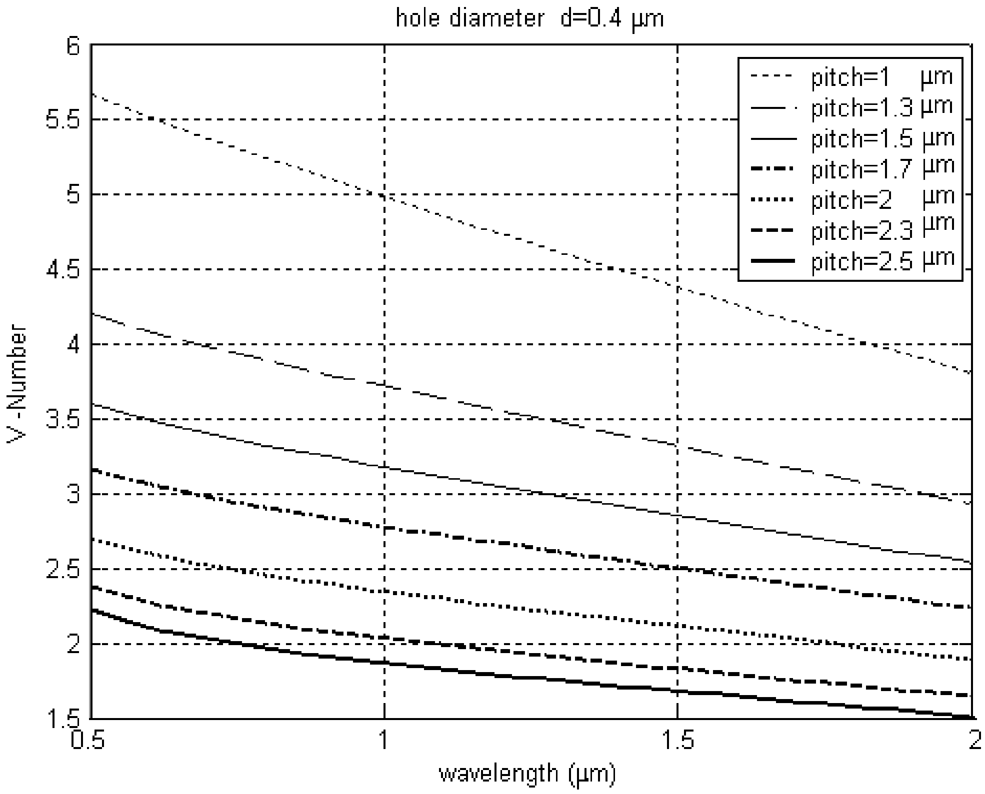

Fig.(3): Calculated V- parameter *vs.* wavelength for PCFs of one ring, one missing hole and d=0.4 μm for different pitch size.

The V- value for proposed PCFs stays nearly constant value even if the wavelength shortened. This result can be explained as the following. Because of the strong wavelength dependence of the n_{eff} for the proposed PCFs (see Fig.2), the special aspect of PCF is that; with decreasing wavelength the effective cladding index also increase, this serving the offset the increase in V-value. This means that PCFs of Λ= 1.7, 2.0, 2.3 and 2.5μm can offer single mode operation from the visible to infrared region, as shown in Fig.3, such a feature is not possible with conventional single mode fiber, where V-value rises as the wavelength shortens and the single mode condition only when $V \leq 2.405$ at specific communication wavelength [3, 13].

Dispersion D(λ):

The chromatic dispersion profile can be controlled by varying any parameter of the PCF, for example the variation in d when the other parameters (Λ, N and MNr) are constant [17], or in general one can manipulate these parameters by many ways in order to increase flatness, at the price of reducing the huge wavelength [18]. The result of this paper shows the dispersion profile under the variations in pitches only, while other parameters (d, N and Nr) are held constant. Contrability of the dispersion is the most important problem in optical communications and specially dependent on which region in the electromagnetic spectrum can be used in telecommunications; for example; laser operated in visible region, Titanium – Sapphire (Ti-Sapphire) laser of 0.8μm and laser diodes which are operated in NIR or MIR region. The chromatic dispersion D(λ) of a PCFs is easily calculated from the real value of the n_{eff} as a function of the wavelength using [8,12]:

$$D(\lambda)=(-\lambda/c)d^2\,\Re(n_{eff})/d\lambda^2 \qquad (3)$$

where c is the velocity of the light in vacuum and ℜ stands for the real part. The material dispersion is directly included in the calculation. According to Eq.3, the chromatic dispersion is calculated from the second derivative of the effective index with respect to wavelength. The pitches is varied to find our aim of this study; dispersion profile, flattened dispersion and zero dispersion wavelength ZDW at a range of wavelength. Fig.4 shows the effect of changing pitches from 1.0μm to 2.5μm for a PCFs (d=0.4μm, Nr=1, MNr=1) on the dispersion profile. It is obviously seen that the pitch Λ dominantly influence the dispersion property. By increasing the pitches the results show the following; *Firstly,* the dispersion profile tend to be near flattened over a range of wavelength (0.9 to 1.9μm) for a PCFs of pitches 1.7, 2, 2.3, and 2.5μm. *Secondly,* for wavelengths more than 1.5μm the level of the chromatic dispersion changes from -200ps/km/nm to near to zero level dispersion. To quantify the performance of our proposed PCF structure of Λ=2.5μm, we have computed the near flattened chromatic dispersion and equal to 10.0 ps/km/nm to -10.0 ps/km/nm over a range of wavelength (λ=0.95μm to 1.4 μm with Λ=2.5μm) and approaches to zero in the range 1.45 to 1.7μm as shown in Fig.4. The results of this paper show also that, both the chromatic dispersion level and flattened property are changed due to the variation of pitches.

To show the influence of the pitches on the ZDW, we draw part of Fig.4 in a small scale as shown in Fig.5, this figure shows that ZDW is also shifted from 1.06μm to 0.965μm due to the decreasing in pitches. That means a blue shift in ZDW is observed due to the variation of the pitches as shown in Fig.6. The change of ZDW per pitch is calculated to be 0.07 for d= 0.4μm, the proposed structure shows a little sensitive to pitches variation comparing with other structures (0.24, for d= 1.51μm) of Kuhlmey *et al* [11].

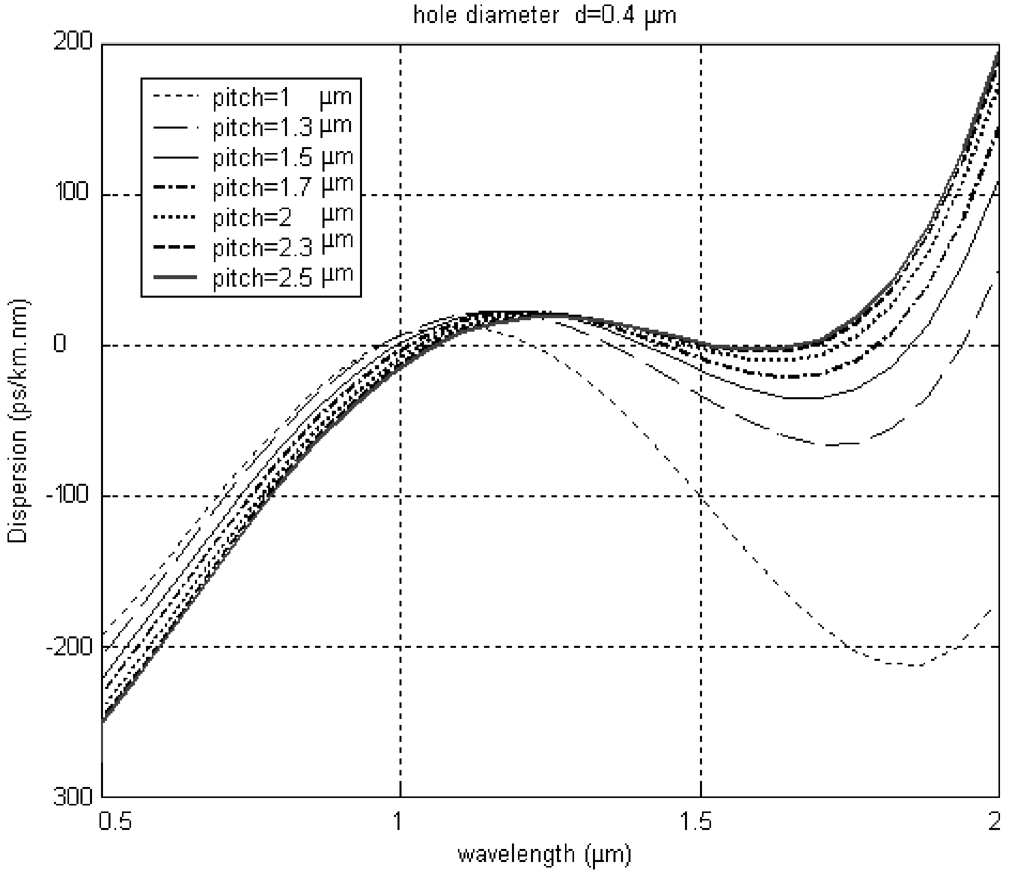

Fig. (4): Calculated Dispersion *vs.* wavelength for PCFs of one ring, one missing hole and d=0.4 μm for different pitch size.

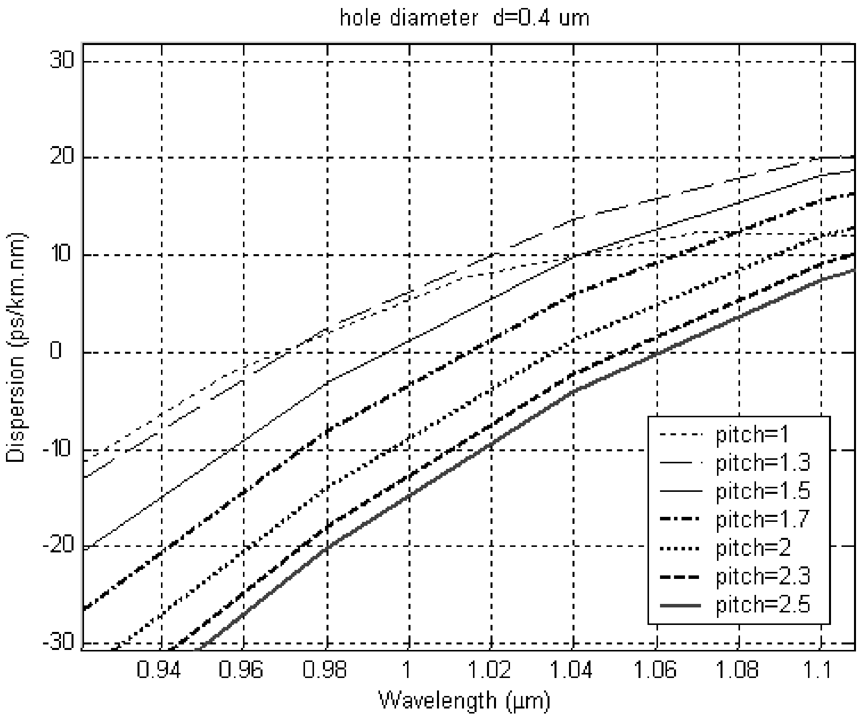

Fig. (5): Dispersion *vs.* wavelength for PCFs showing the influence of the pitches on the ZDW.

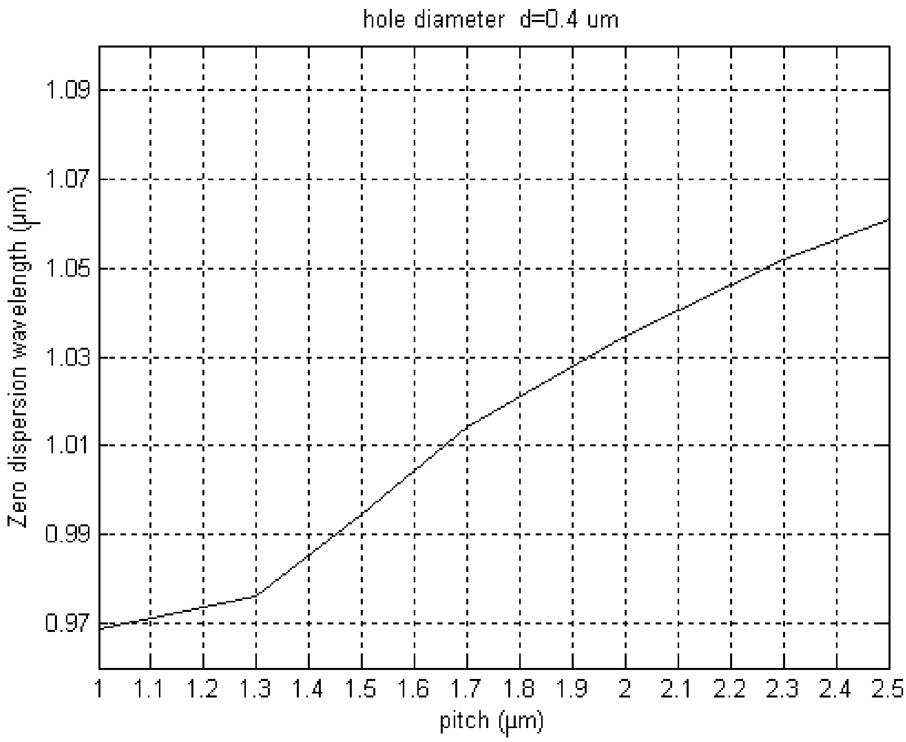

Fig. (6): Zero dispersion wavelength *vs.* pitch size for PCFs of one ring, one missing hole and d=0.4 μm.

Confinement loss (L):

The losses in PCFs occur for a number of reasons, such as intrinsic material absorption loss, structural imperfection loss, Rayleigh scattering, and confinement loss [18]. Confinement loss is an additional form of loss that occurs in single material fibers. PCFs are made of pure silica, so all mode are inherently leaky because the core index is the same as the index of the outer cladding region without air holes. [9,12,18].

It is very important to determine the confinement loss (for a given communication wavelength) that are intrinsically related to the structure of the PCF. That means the level of the confinement loss is important parameter to design a PCF with a finite number of air holes and rings. The confinement loss is deduced from the value of the n_{eff} as [5,9,12]:

$$\mathbf{L(\lambda)= [40\pi/ \lambda ln(10)]Im(n_{eff}) \times 10^{9}} \qquad (3)$$

Where λ in micrometer, L(λ) in dB/km and Im stands for the imaginary part**.** We have shown already that the proposed PCFs structure can exhibit near to/or flattened dispersion. In practical application and when the fiber is used in communication; near flattened, flattened or zero dispersion PCF may not be enough for justify the usefulness of the PCF. Low confinement loss are needed for some particular application like nonlinear effects[1]. Fig.7 shows the confinement losses for the fundamental mode of the proposed PCFs. The PCFs under investigation are of one ring of holes with same air hole diameter with various pitches. Fig.7 shows that as the pitch increases the confinement losses decreases. The PCF of larger pitch has lower confinement losses over a wide range of wavelength, from 0.5μm to 2.0μm. This result can be explained as the following; if we are looking to the Fig.2 and Fig.7 one can obtain that the real part of the effective index PCF of Λ=2.5μm (which is a larger pitch in our study) for the fundamental mode, tends to the refractive index of silica. So the propagation becomes increasingly parallel to the fiber axis. Interaction with the confining structure is thus minimized [11]. Additionally at communication wavelength of 1.5μm the calculated losses for the PCF of (Λ=2.5μm and d/Λ <0.4 for the fundamental mode) is around 0.14dB/m (Fig.8), which is a lower losses comparing with published data 1.0dB/m of PCF (Λ=2.5μm and d/Λ <0.4) at the same window [11]. While in communication window 0.8μm wavelength, of (Ti-Sapphire) laser, the same structure gives losses equal to 0.065dB/m. Finally all PCFs under investigation show lower losses at the communication wavelength 0.8 μm of (Ti-Sapphire) laser. Therefore PCFs with more rings of holes may be necessary to reduce the confinement loss [11].

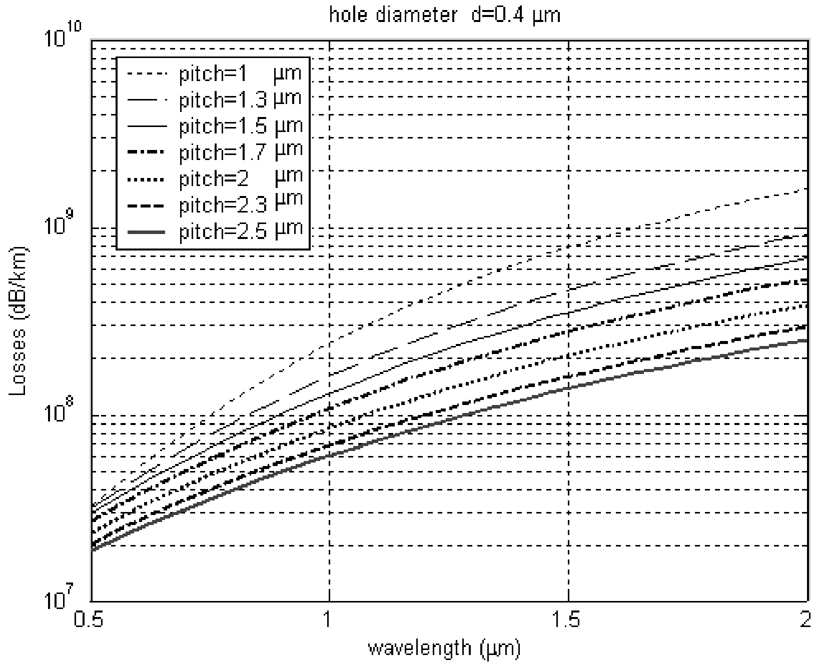

Fig. (7): Confinement loss for the fundamental mode of PCFs of one ring and d=0.4µm:for different pitch size as a function of λ

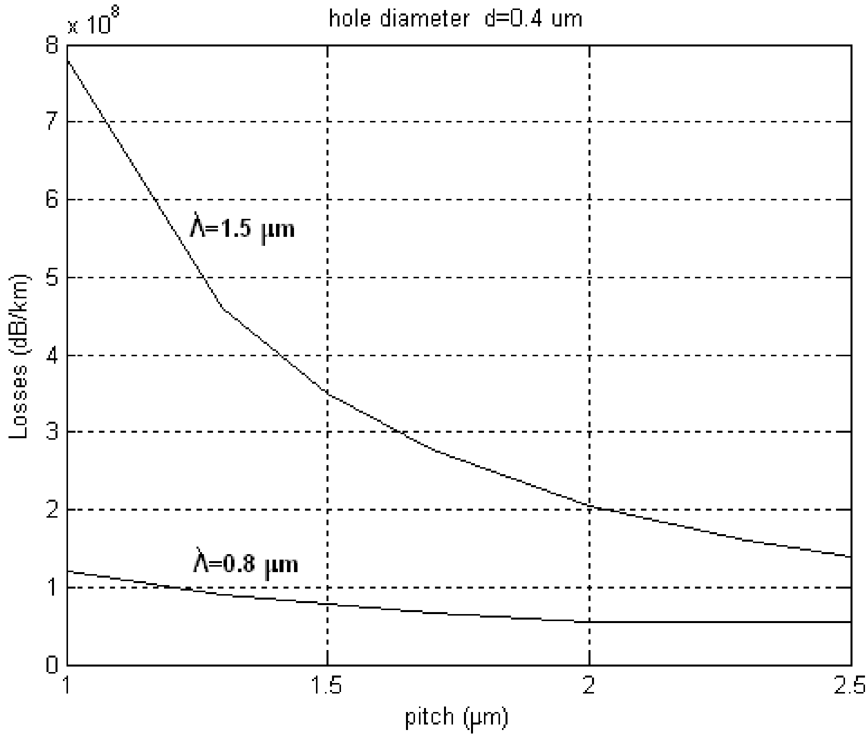

Fig. (8): Confinement loss for the fundamental mode as a function of pitches for a PCFs of one ring and d=0.4µm: at wavelength
0.8µm and 1.5µm.

Conclusions:

In summary**,** the proposed structure**s** of PCFs of (d=0.4µm, Nr=1, MNr=1 and Λ= 1.0µm to 2.5µm) are studied. Structures of Λ= 1.5µm to 2.5µm shown to be single mode operation over a wide range of wavelength. The dispersion curve to be flattened or near flattened is sensitive to the pitch size. Blue shift in zero dispersion wavelength is obtained due to decreasing in pitches. PCF of Λ=2.5µm offers near flattened dispersion over 0.950 µm to 1.4µm wavelength with lower confinement losses at all wavelengths under study.

Other designs of PCFs which can exhibit ultra-flattened dispersion with low confinement losses, based on the elliptical air holes in the cladding [1] or two missing circular holes in the center of the PCF [19] are currently under consideration.

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تأثير حجم الخطوة على شكل منحني التشتت للاطياف البلورية الفوتونية

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الملخص

في هذا البحث تم دراسة تأثير حجم الخطوة على شكل منحني التشتت للالياف البلورية الفوتونية. (٧) ألياف والتي يتمثل تصميمها بحلقة واحدة من الفجوات الهوائية وهذه الفجوات ذات قطر ٠,٤ مايكرون، مع غياب فجوه هوائية واحدة في مركز الليف، قد تم البحث فيها عند تغير حجم الخطوة من ١,٠ مايكرون الى ٢,٥مايكرون.

أظهرت هذه الدراسة ان ألالياف التي لها حجم خطوة ١,٧ و٢,٠ و٢,٣ و٢,٥ مايكرون تتميز بانها تعمل بنمط منفرد على مدى واسع من الاطوال الموجية (من المنطقة المرئية الى المنطقة تحت الحمراء)، وان شكل منحني التشتت يقترب الى التسطح لمدى واسع من الاطوال الموجية (٠,٩٥ الى ١,٤٥) مايكرون. في حين ادى التغير قي حجم الخطوة الى دفع الطول الموجي للتشتت الصفري الى الموجات الاقصر. أشارة النتائج الى نقصان كبير في خسارات الحصر للنمط الاساس لليف البلوري الفوتوني والذي فيه حجم الخطوة ٢,٥ مايكرون. جميع الالياف تحت الدراسة أظهرت نقصان كبير في خسارات الحصر عند موجة ارسال ٠,٨ مايكرون لليزر (تيتانيوم– ياقوت الازرق) مقارنة مع موجة ارسال ١,٥ مايكرون.