# Design and analysis of Large Pitch Photonic Crystal Fibers ( LPF PCF )for robust Single Mode operation

# تصميم وتحليل الالياف البلورية الفوتونية ذات مسافة الخطوة الكبيرة (LPF PCF) للعمل بصورة اكثر تاكيد كاحادية النمط

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## Abstract

Since a Single-Mode (SM) output ensures high beam quality and excellent stability, the SM operation in Large-Mode-Area (LMA) fiber amplifiers and lasers is critical. This paper presents a numerical simulation of single mode operation for Large Pitch Photonic Crystal Fibers. Using COMSOL Multiphysics running with MATLAB, the confinement of the fundamental and higher-order modes in the core of fiber are obtained for different wavelengths, pitch sizes and air-holes diameter. In a certain point of air-holes diameter for different Large Pitch Photonic Crystal Fibers, the avoided crossing between HOMs has been occurred. In this point, the confinement loss of HOMs is increased which is more ensure for SM operation.

## الخلاصة

بما ان الاشارة الخارجة الاحادية الطور تضمن نوعية الاشعاع العالية والاستقرارية الممتازة فان العمل كاحادي الطور في الالياف البلورية الفوتونية ذات المساحة الكبيرة في المضخمات او الليزر اصبحت جدا مهمة. في هذة البحث تم تقديم محاكات عددية للعمل كاحادي الطور في لالياف البلورية الفوتونية ذات مسافة الخطوة الكبيرة. باستخدام برنامج الكومسول (COMSOL) بواسطة ربطه مع الماتلاب (MATLAB) فان انحصار النمط الاساسي والانماط ذات الدرجات العالية داخل قلب الليف البلوري الفوتوني قد تم حسابة لمختلف الاطوال الموجية وحجم الخطوة وقطر الفجوة الهوائية. وقد وجد ان خلال قطر فجوة هوائية لمختلف الالياف البلورية الفوتونية ذات مسافة الخطوة الكبيرة هناك تقاطع بين الانماط ذات الدرجات العالية.وفي هذة التقاطع انحصار الانماط ذات الدرجات العالية قليل جدا وهذا يودي لضمان اكثر لعمل على احادي الطور.

## 1. Introduction.

In recent years, Photonic crystal fibers (PCFs) have attracted great attention due to their interesting properties, such as endless single-mode operation, unique dispersion and nonlinear characteristics [1].

There are basically two types of photonic crystal fibers which are called solid core photonic crystal fiber SC- PCFs and hollow core photonic crystal fiber HC-PCFs. The cladding structure is formed by a periodic hexagonal pattern of air-holes around the central core. The air-holes lower the effective refractive index of the cladding. Hence, light is guided within the PCF by total internal reflection TIR, this type is also called an index guiding PCF. While for HC-PCFs, because its core index (air) is lower than the effective index of the cladding (periodic array of air holes), guidance via TIR is impossible, so the only possible guidance mechanism is photonic band gap (PBG) effect. By this effect the light is guided in a low index region [2, 3].

The most interesting features made possible by the formation of holey cladding in photonic crystal fibers (PCFs) is a single mode property over a large wavelength range, down to visible regimes ,which is called endlessly single mode (ESM) property [4,5], achieved simultaneously with yet a relatively large mode area (LMA). The ESM property is believed to be attributed to the fact that the effective refractive index of the holey cladding gets closer to the one of the core when wavelength gets smaller [4,5]. Such structural dispersion reduces the index contrast between the core and the holey cladding and so compensates the decrease of wavelength [4,6] when one moves to short wavelength regime. This effect is stronger for smaller air filling factor (i.e. smaller relative hole's size). Such situation causes challenge in designing commercial PCF as small relative hole's size implies large confinement loss.[4,6]

In this paper, we consider not just strictly single-mode fibers, but also so-called endlessly single-mode fibers which support only one guided mode over all wavelengths. The numerical results in this paper have been conducted with the full vector FEM combined with perfectly-matched layers (PMLs) [5], for which we employed a commercial package, COMSOL MULTIPHYSICS™. The main purpose of the proposed PCF structure presented in Fig. 1 is to achieve endlessly single-mode operation with improved beam quality by decreasing the confinement losses of high order modes.

## 2. Method analysis.

The Finite Element Method (FEM) is popular and appealing for numerical electromagnetic simulation due to its many merits. It has been one of the major tools for the analysis and understanding of PCFs [7,8,9]. The discretization scheme can be derived from the Helmholtz equations or Maxwell's equations directly.

The mode analysis is made on a cross-section in the xy-plane of the fiber where we employ the FEM to solve Maxwell's equations by accounting for the adjacent subspaces. The overlap of FM or HOMs inside the core of PCF is evaluated by the inclusion of PML in the FEM. The PML consists of anisotropic permeability and permittivity that matches the outside medium in order to prevent reflections [5]. The wave propagates in the z direction and has the form

$$H(x,y,z,t) = H(x,y)e^{j(wt-\beta z)} \qquad (1)$$

where ω is the angular frequency and β the propagation constant. An eigenvalue equation for the magnetic field H is derived from Helmholtz equation

$$\nabla \times (n^{-2}\, \nabla \times H) - k_0^2 H = 0 \qquad (2)$$

which is solved for the eigenvalue $\lambda = -j\beta$. Where n is the refractive index and $k_0$ is wave-number in the vacuum.

As boundary condition along the outside of the cladding the magnetic field is set to zero. Because the amplitude of the field decays rapidly as a function of the radius of the cladding this is a valid boundary condition [5, 9, 10].

## 3. Guided Modes in PCFs

The core index for an index-guiding PCF is greater than the average index of the cladding because of the presence of air-holes. The fiber can guide the light by total internal reflection as a standard fiber does. That is, the guided light has an effective index $n_{eff}$ that satisfies the condition

$$n_{co} > n_{eff} = \frac{\beta}{k_0} > n_{FSM} \qquad (3)$$

where β is the propagation constant along the fiber axis, $n_{co}$ is the core index, and $n_{FSM}$ is the cladding effective index of the FSM [11,12].

The important difference for large pitch PCFs with respect to conventional fibers that PCFs can be designed to be Endlessly Single-Mode (ESM) that is only fundamental mode can be propagated depends on the value of wavelength and pitch. If there is a large difference in the effective index between the higher order and the fundamental mode, the confinement loss of the higher order modes are much more than that of the fundamental mode then these fibers are likely to be single mode in practice [11, 13].

## 4. Effective Mode Area in PCFs.

The effective area of the fiber core $A_{eff}$ is defined as,

$$A_{eff} = \frac{\left(\iint_s |E_t|^2\, dxdy\right)^2}{\iint_s |E_t|^4\, dxdy} \qquad (4)$$

where $E_t$ is the transverse electric field vector and S denotes the whole fiber cross section [10,11]. However, the effective area enlargement can be detrimental for the active fiber Single-Mode (SM) behavior, which is mandatory for the high laser beam quality required in many applications. Double-Cladding Photonic Crystal Fibers (DC-PCFs) have been demonstrated to be a valuable solution to these issues, being capable to support SM guiding even with very large active core diameters [8, 14, and 15]

## 5. Design of the PCF

We consider a photonic crystal fiber with triangular lattice pattern of holes as shown in Fig. 1, where'd' is the hole, Λ is hole pitch or periodicity of the structure, $n_{core}$ is the refractive index of core material.

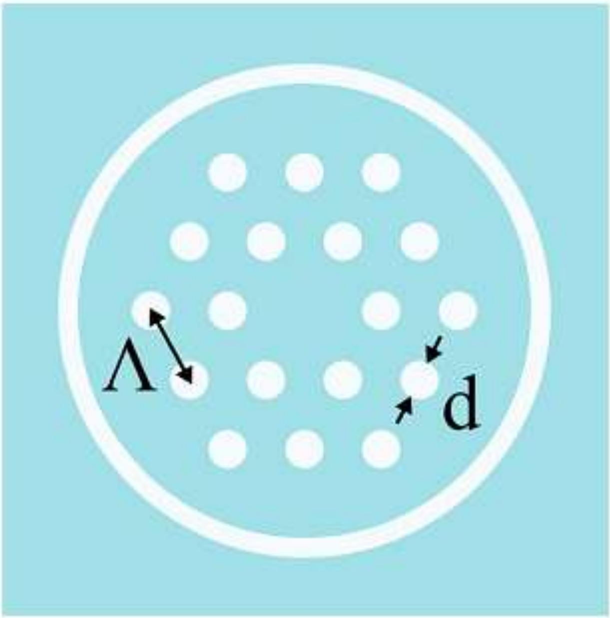



Fig. 1. Schematic design of a two-ring large pitch fiber surrounded by an air-clad.

In order to investigate the single-mode condition, fundamental mode is required to be solved over a wide range of wavelengths. In a conventional fiber, the number of bound modes is governed by V- number, which increases with decrease of wavelength. For such pattern, V-parameter can be given as-

$$V = \frac{2\pi}{\lambda}\rho\left(n_{core}^2 - n_{fsm}^2\right)^{0.5}$$

where the ρ is the core radius, $n_{core}$ is the core index, $n_{fsm}$ is cladding layer index [16] .

## 6. Results and discussion

In this paper, the COMSOL Multiphysics interfacing with MATLAB had been using in this simulation. The first step of simulation is to search to fundamental mode and higher order modes depending on effective index manually using only COMSOL Multiphysics without interface. Also this step have been investigated for the first time, to the authors' knowledge .The field distribution of the fundamental mode and higher modes for different pitch size are shown in the Fig. 2.

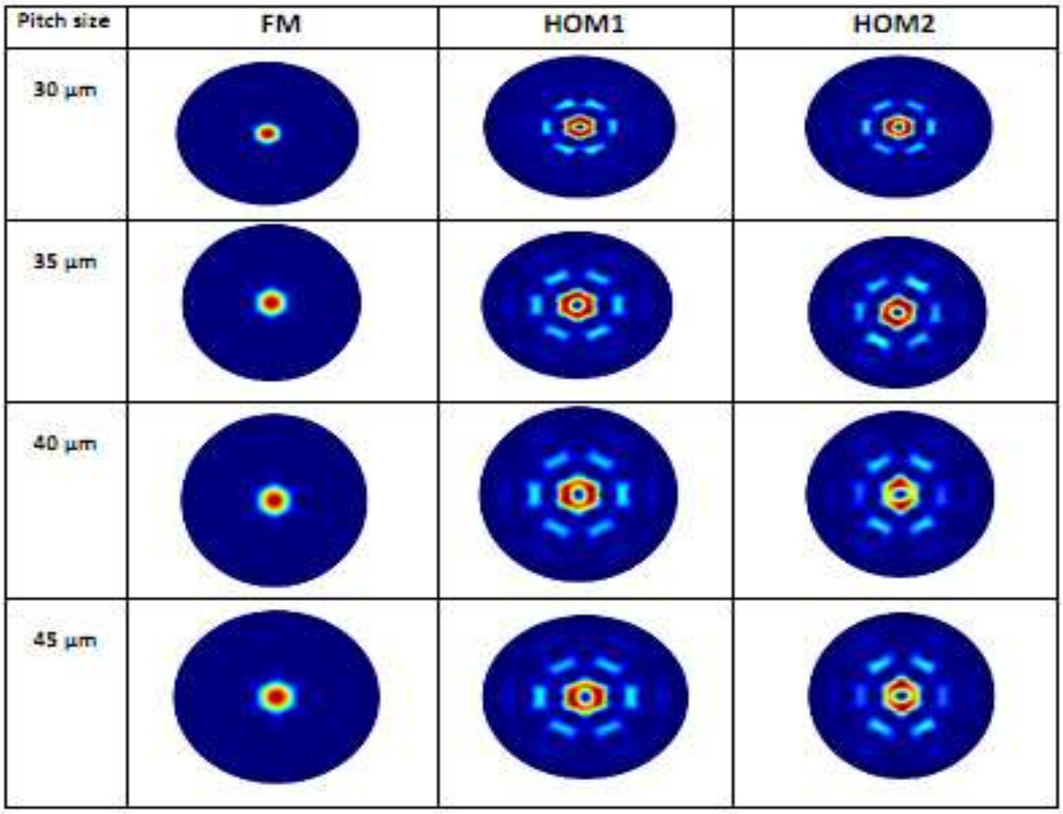
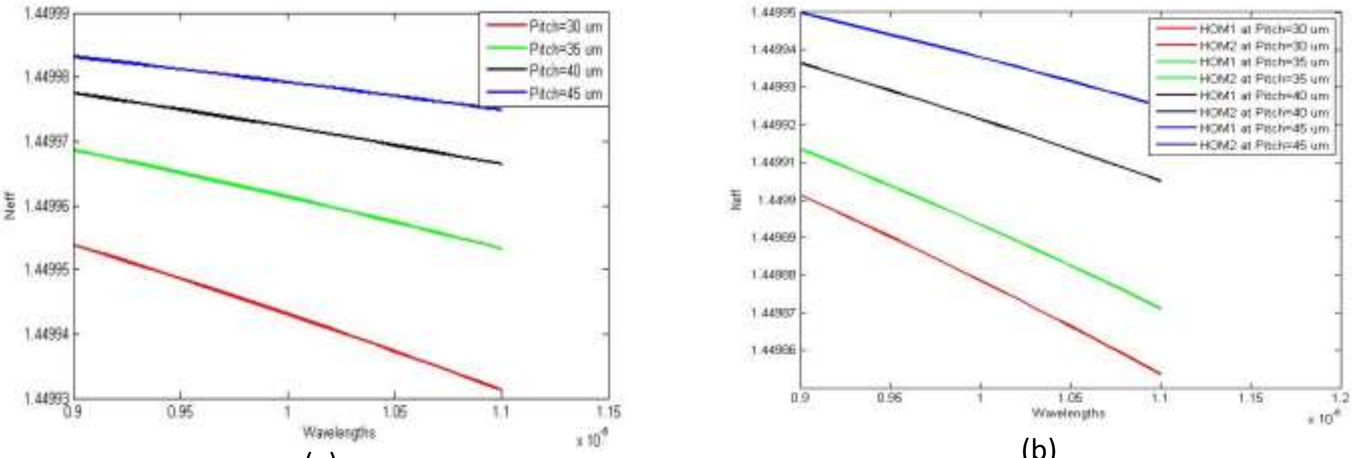



Fig. 2. The field distribution of the fundamental mode and higher modes for different pitch size

Because the wavelengths are the most important parameter of guiding mode for PCFs [7, 8], the effect of wavelength on the effective index and the overlap integral for different pitch size had been obtained. The range of the wavelengths of high power lasers which are mostly used today are between (900-1100) nm [7, 8].The relations of effective index

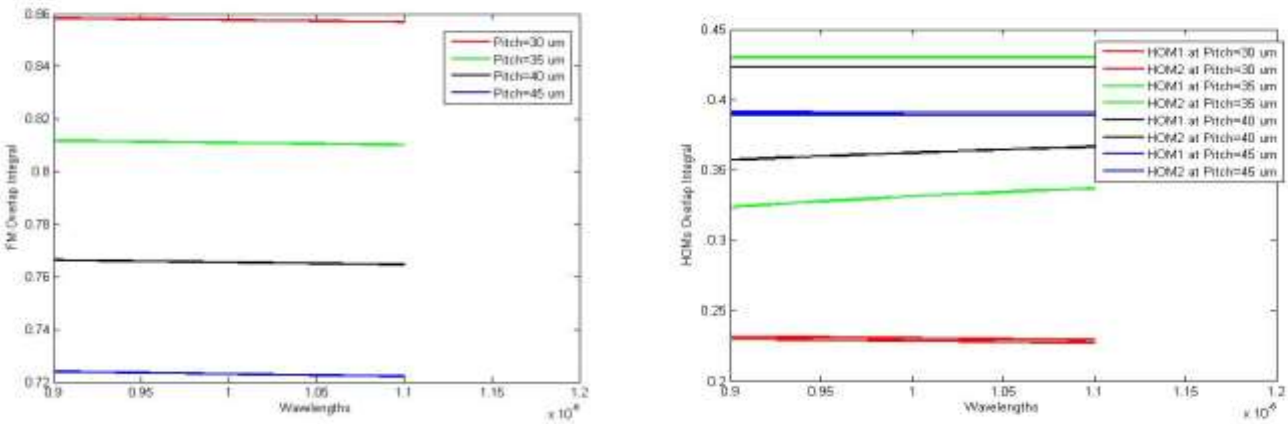
of SMs and HOMs for different pitch size and different wavelengths are shown in the Fig. 3. The effective index of HOMs are more decrease with increase of wavelengths comparing with the effective index of FMs.




(a) (b)

Fig. 3. The effective index of a) SMs and b) HOMs for different wavelengths at different pitch size.

Fig.4 shows the overlap integral for FMs and HOMs for different pitch size and different wavelengths. In this figure the overlap integral for SMs are approximately constant through this range of wavelengths but it decreases with increasing the pitch size. For the HOMs, the overlap integral increases with decreasing the pitch size and some of them are more overlap inside the core than what is expected like one of the HOMs of pitch size 35 μm and 40 μm.




(a) (b)

Fig. 4. The overlap integral for a) FMs and b) HOMs for different wavelengths at different pitch size.

Since the effective area of the FMs is playing as necessary parameter for the high power fibers, it had been calculated for each pitch size of different fibers. The larger effective area leads to increase of HOMs and avoiding of non-linear effect so it is required to get equilibrium between them. Fig. 5, shows the effective area of SMs with different Pitch size.

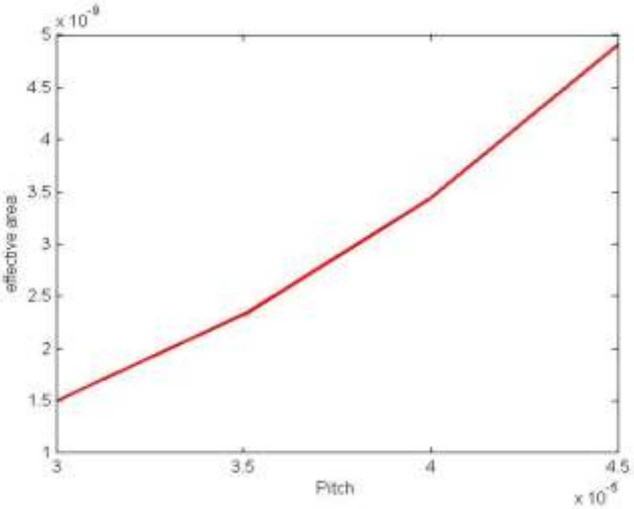
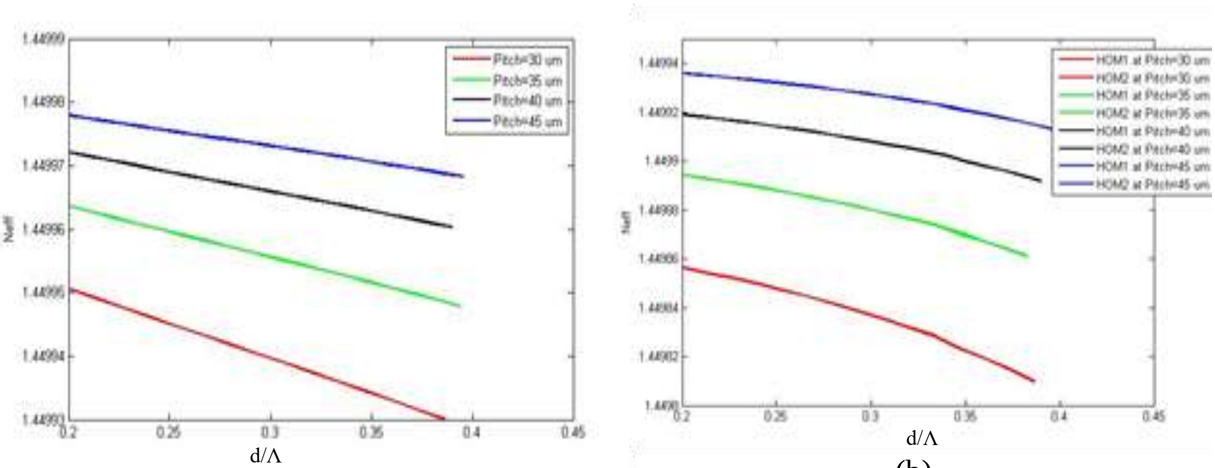



Fig. 5 The effective area of SMs with different Pitch size.

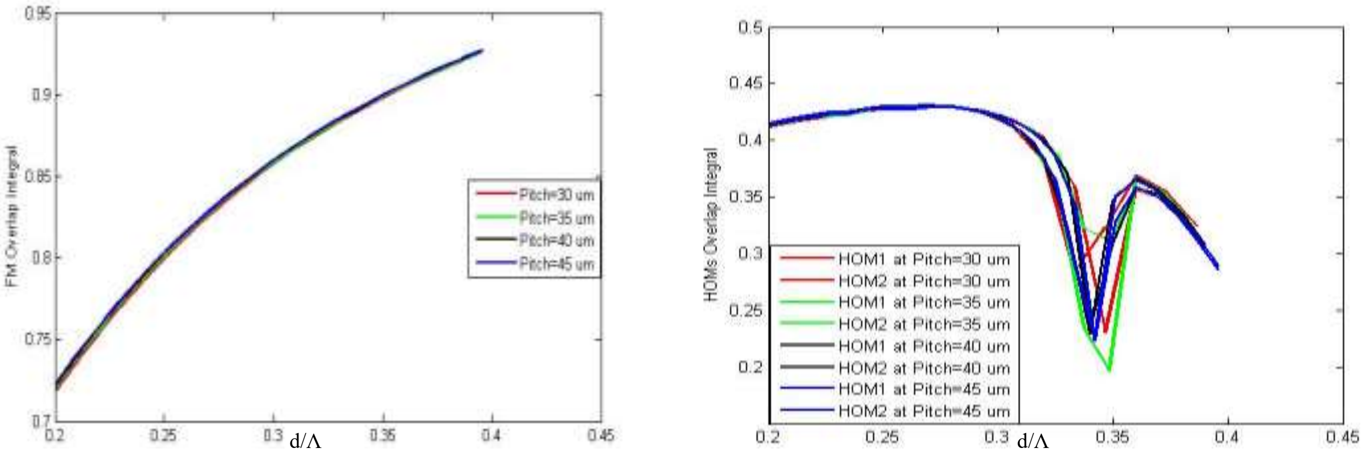
In any type of fiber, the ratio of diameter to pitch size (d/Λ) are most effect to properties of FMs and HOMs. It was found that the best range of d/Λ for single mode operation is between (0.2 – 0.4). When the d/Λ is more than 0.4 then the overlap integral of HOMs inside the core will be more 0.5 and no single mode operation. When the d/Λ is less than 0.2 then the fabrication of fiber will be more complicated. Fig. 6, shows the effective index of SMs and HOMs for different pitch size and different ratio of d/Λ .




(a) (b)

Fig. 6 The effective index of a) SMs and b) HOMs for different ratio of d/Λ at different pitch size.

Fig. 7, shows the overlap integral for SMs and HOMs for different pitch size and different ratio of d/Λ. The overlap integral for FMs inside the core are increased with increasing the d/Λ but for the HOMs there are some disturbing to be overlapped inside the core because of the avoiding crossing [17]. In the reference [17] the avoiding crossing represent as unwanted effect because it disturb the single mode operation. In our work, we search to find the range that HOMs have avoiding crossing but SMs are not. So in this way, SMs can be not effected and there will be more loss to HOMs. As a result the single mode operation will be more insure.




(a) (b)

Fig. 7 the overlap integral for a) SMs and b) HOMs for different pitch size and different ratio of d/Λ

Fig.8, shows the avoiding crossing for different types of PCFs. All the different types of photonic crystal fibers show it at d/Λ approximately equal 0.345

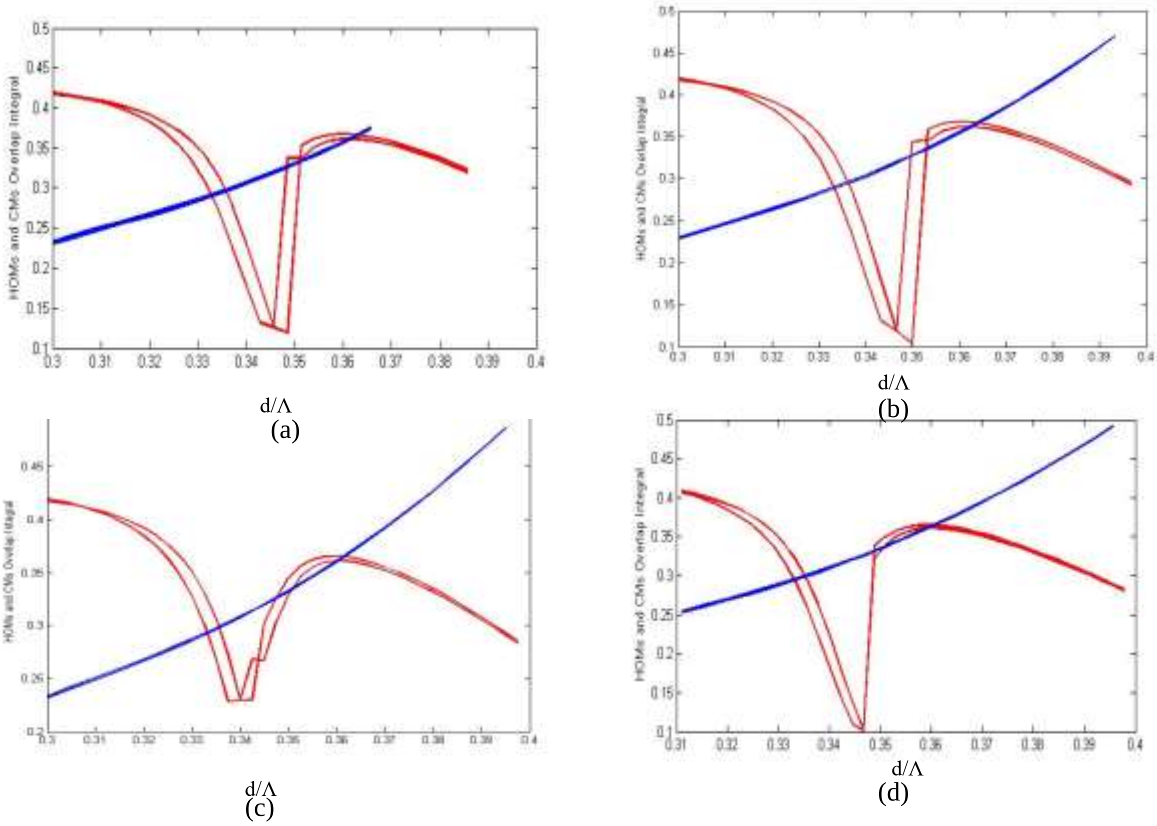



Fig. 8. The avoiding crossing for different types of PCFs. The pitch are a) 30 μm b) 35 μm c) 40 μm and d) 45 μm

## 7. Conclusion

The single mode operation for different Large Pitch Photonic Crystal Fibers had been study using COMSOL MULTIPHYSICS. The single mode operation had obtained by calculating the overlap integral of FMs and HOMs inside the core. If the overlap integral of FMs are greater than 0.8 and HOMs are less than 0.5 then the fiber is single mode operation else it are not. It is found that the overlap integral is not effected with change the wavelength but strongly effected with change to the ʌ/d. For the certain type of Large Pitch Photonic Crystal Fibers (i.e. certain of ʌ/d, the avoiding crossing had observed with HOMs but not with FMs. That is meaning we can get more loss for HOMs without effecting to FMs if we use this type of Large Pitch Photonic Crystal Fibers.

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