Design and Analysis of 19 cell PCF for Robust Single Mode Operation usingAvoided-Crossing Modes Approach

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Abstract

Double-cladding large mode area rod-type photonic crystal fibers have become a key component for power scaling in high power fiber laser systems to provide an ultra large effective area. By a careful design, the single-mode regime can be obtained insuch large core active fibers. In this paper, the 19-cell photonic crystal fibers with 3 rings in the fiber inner cladding have been investigated with the avoided-crossing approach, in order to find guidelines for the design of single-mode fibers. The air-hole diameter and the wavelength have been changed.In a certain point of air-holes diameter and the wavelength for 19cell PCF, the avoided crossing between HOMs has been occurred. In this point, the confinement loss of HOMs is increased which is more ensured for SM operation.

Key words: Photonic crystal fiber, single mode operation, multimode fiber, higher order modes delocalization, 19-cell

الخلاصة

الاليياف البلورية الفوتونية ذات النوع الصلب والاطار المضاعف اصبحت الاداة المفتاح لتحسين الياف القدرة العالية في انظمة الليزر لتوفير مساحة فعالة عالية جدا. بواسطة تصميم معين ،ممكن الحصول على نمط احادي الطور في قلب هكذا الياف فعالة. في هذا البحث الالياڤالبلورية الفوتونية ذات 19 خلية مع ثلاث حلقات من الفجوات في اطار الالياف تم التحقق منها مع طريقة الاطوار المتقاطعة المتحاشية لكي نجد دليل لتصميم الياف احادية الطور.قطر الفجوة الهوائية والطول الموجي قد تم تغيرهم خلال المحاكاة. في نقطة معينة من قطر الفجوة الهوائية والطول الموجي للالياف البلورية الفوتونية،الاطوار المتقاطعة المتحاشية قد تم الحصول عليها. وفي هذا النقطة، فان تداخل التوافقيات ذات الدرجة العالية داخل قلب الفايبر سوف يقل وهذا يودي الى زيادة نسبة عملية احادية الطور

الكلمات المفتاحية:الالياف البلورية الفوتونية، عمل احادي الطور، الياف متعددة الاطوار،تقليل اطوار ذات الدرجة العالية،19-خلية

1. Introduction

Photonic crystal fibers (PCFs) have become a field of ample study and research due to their essential application in high power laser devices and unique interesting properties and nature of its structure(Taha ,2013). Depending on their multilayer structure, the travel of the electromagnetic wave through PCFs rests on the alternation of refractive incident angles of those multilayer materials(Karmakar, 2012).

A single mode property over a large wavelength range, down to visible regimes,which is called endlessly single mode (ESM) property (Birks,1997 ,Akowuah,2009),achieved simultaneously a relatively large mode area (LMA), isan essential property features conceivably created in photonic crystal fibers (PCFs). The contribution of the ESM property is greatly recognized to the fact when wavelength gets smaller,effective refractive index of the holey cladding gets closer to the one of the core (Birks,1997 ,Akowuah,2009),As a result, the index contrast between the core and the holey cladding and so compensates the decrease of wavelength when moving to a short wavelength regime. For Smaller air filling factor, the effect becomes stronger. The effect has led to a great challenge in designing PCF since small relative hole size imply large confinement loss(Birks,1997 , demgil, 2012).

In this paper, we consider single-mode fibers. The numerical results in have been conducted with the full vector FEM combined with perfectly-matched layers (PMLs)(Taha ,2013), for which we employed a commercial package, COMSOL MULTIPHYSICS™. The main purpose of the proposed PCF structure presented in Fig. (1) is to achieve single-mode operation with improved beam quality by decreasing the confinement losses of high order modes

2. Method analysis.

In order to understand and analyze the PCF's, a mathematical tool is essential for this analysis. One of the common and popular tools for analysis is the Finite Element Method (FEM). Due to its advantageous numerical electromagnetic simulation capability (Poli, 2011, Coscelli ,2012, Coscelli ,2013). The discretization scheme can be derived from the Helmholtz equations or Maxwell's equations directly.

A cross section of a fiber is placed on the xy-plane for mode analysis. Accounting adjacent subspaces, it is essential to solve Maxwell's equation by using FEM. The wave propagates in the z direction and has the form

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

Where: ω is the angular frequency.
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.
k_0: is wave-number in the vacuum.

The insertion of PML in the FEM evaluates the overlap of FM or HOMs inside the core of PCF.The PML consists of anisotropic permeability and permittivity that matches the outside medium in order to prevent reflections(Akowuah,2009).

To solve the equation, a boundary condition is essential; the magnetic field along the outside of the cladding is set to zero, since the amplitude of the field decays rapidly as a function of the radius of the cladding which makes this a valid boundary condition (Akowuah,2009, Coscelli,2013, The COMSOL Multiphysics, 2012).

3. Guided Modes in PCFs

The presence of air-holes causes the core index for PCF's index guiding to be higher than almost the average index of the cladding. Any standard fiber can guide the light through total internal reflection.The fiber is used to the same reality to guide light. A condition is set to the effective index $n_{eff}$of the guided light to fulfill(Pourmahyabadi,2009, Saitoh,2005):

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

Where: β is the propagation constant along the fiber axis,
n_{co} is the core index.
n_{FSM} is the cladding effective index of the FSM.

Depending on the wavelength value and pitch, only fundamental mode can be propagated, therefore; PCFs can be designed to be Endlessly Single-Mode (ESM) which is an essential difference for large pitch PCFs with respect to the existent fibers. The fundamental mode is expected to be a single mode in practice if, there is a large difference in the effective index between the higher order and the fundamental mode, and the confinement loss of the higher order modes which are much more than that of the fundamental(Pourmahyabadi,2009,Poletti , 2005).

4. Effective Mode Area in PCFs

The effective area of the fiber core A_{eff} is defined by equation (4)(Saitoh,2005, Poletti, 2005):

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

Where: E_t is the transverse electric field vector
S denotes the whole fiber cross section.

For various applications, a high laser beam quality is required, therefore; it is unfavorable to enlargethe effective area for the active fiber Single-Mode (SM) behavior for these required applications. In order to solve this issue, a Double-Cladding Photonic Crystal Fibers (DC-PCFs) is introduced where it has been demonstrated that (DC-PCFs) isa valuable solution to these issues. Double-Cladding Photonic Crystal Fibersare capableto backup SM guiding although large diameters of active core are present(Coscelli,2012,Russel,2006, Hansen,2008).

5-PCF with Crossings and avoided crossings

Crossings and avoided crossings are a well understood phenomenon in photonic bandgap fibers (Smith,2003,West, 2004, Noordegraaf,2008), where they lead to a reduced transmission within the bandgap. At a crossing, two modes have identical effective indices but their modal overlap remains zero, i.e. they are still orthogonal to each other. Therefore, there is no interaction between the crossing modes, and the crossing can be simply described as a fortuitous coincidence of the index of refraction of two modes with different dispersion characteristics without further physical consequences (F. Stutzki,2011).

On the contrary, when avoided crossings (or anti-crossings) occur, two orthogonal modes evolve to show nearly identical transverse profiles (in spite of their effective refractive index not being equal, hence avoided-crossing). Progressively, during the avoided-crossing, the modes exchange their roles and their effective indices diverge.

Surrounding the core structure of a PCF with a pump core leads to a completely new structure, in which core and cladding modes can interact. With changing air-clad diameters, wavelength or pitch size, the effective index of a core guided mode basically remains constant while that of the cladding modes will be changed. Therefore, at some point, the effective index of the clad modes will reach the effective index of the FM or HOMs. In our work, there are no avoided crossings with FM but only with HOMs. It can be useful to increase the overlap between FM and HOMs. In the latter case, the shapes of both modes converge and, finally, the former clad mode takes over the role of the HOM while the former HOM is delocalized from the core and becomes a cladding mode(F. Stutzki,2011).

6. Design of the PCF.

In this paper the 19-cell photonic crystal fibers with 3 rings in the fiber inner cladding have been considered, as shown in the 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.

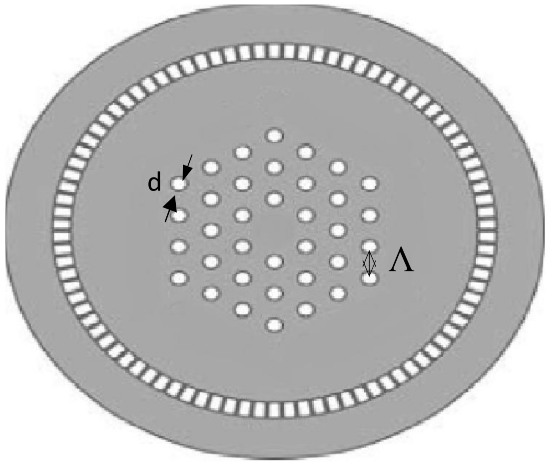


Fig. (1): Schematic design of 19-cell photonic crystal fibers with 3 rings surrounded by an air-clad.

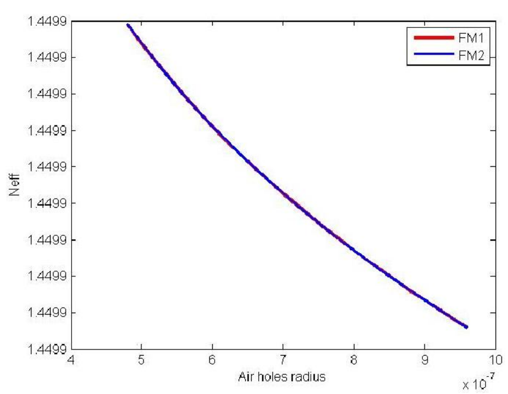
In order to investigate the single-mode condition, fundamental mode is required to be solved over a wide range of wavelengths. The number of bound modes is governed by equation. (1)(Karmakar, 2012):

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

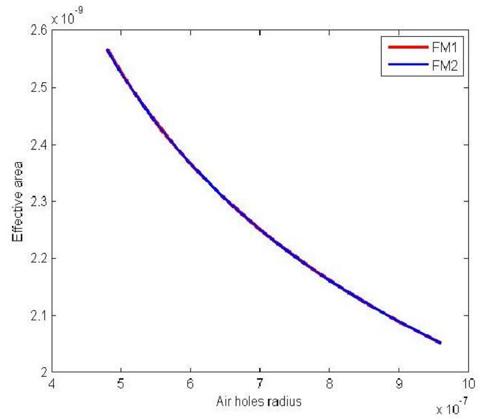
Where: V- number, which increases with decrease of wavelength.
ρ is the core radius, n_{core} is the core index, n_{fsm} is cladding layer index.

7. Results and discussion.

The COMSOL Multiphysics interfacing with MATLAPare used in this simulation. The important parameters of 19 cell PCF design with 3 rings are wavelength=1030e-9, pitch=12 µm and air cladding radius= 85 µm. Starting the simulation by changing the air holes radius from 0.48 µm to 0.96 µm or the ratio (d/ Λ) from 0.08 to 0.16 to obtain the effective index N_{eff}, effective area and overlap integral of the fundamental Modes, as shown in Fig.(2).



(a)



(b)

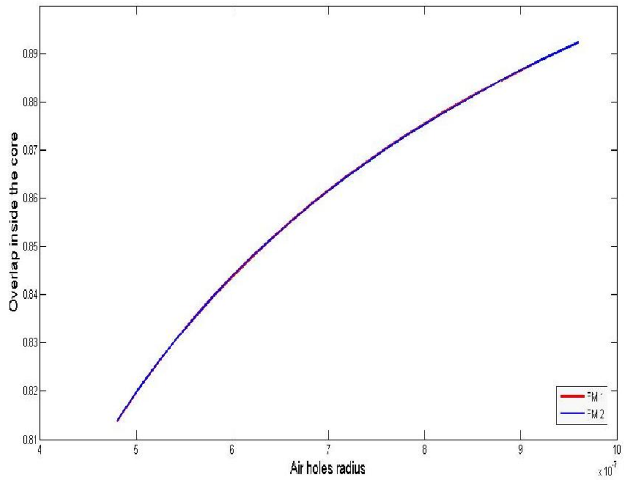
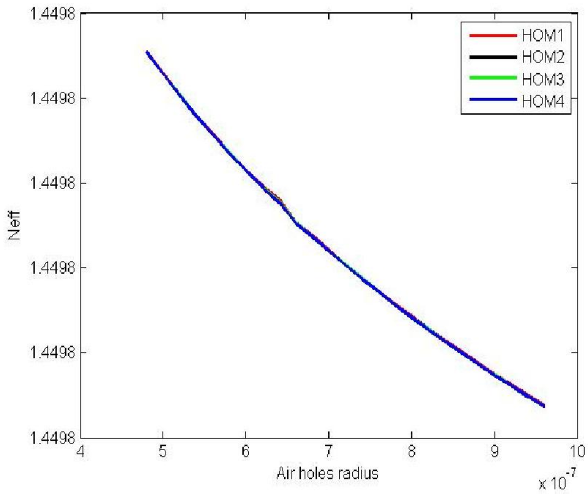
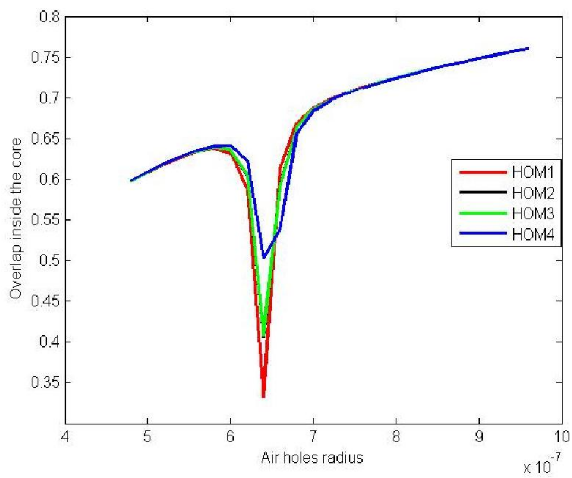


Fig. (2): (a) the effective index N_{eff} (b) effective area and (c) overlap integral of the fundamental Modes with respect to different air holes radius of the

The same procedure was applied to find the effective index N_{eff} and overlap integral for higher order modes (HOM), as shown in Fig. (3).



(a)



(b)

Fig.(3): (a) the effective index Neff and (b) overlap integral of the Higher order Modes with respect to different air holes radius of the PCF

In above results, there is an avoiding crossing in HOMs but not in FMs and this avoiding crossing is just in the case where the air cladding radius is 85 µm. This property can be useful to increase the deference of overlap integral between FMs and HOMs. If it is designed with air holes radius at which minimum overlap integral is obtained, the mode operation will be more close to single mode operation.It was important to check the avoiding crossing for different air cladding radius. In the following results with different air cladding, there are no avoiding crossings in HOMs.

Three different value of air cladding radius had been chosen, one is 72 µm which is the large difference compared to 85 µm, and the second and third are close to 85 µm which are 83 µm and 87 µm, respectively, as shown the Fig. (4).

Because the wavelengths are the most important parameter of guiding mode for PCFs (Coscelli,2013, The COMSOL Multiphysics 2012).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 (Coscelli,2013, The COMSOL Multiphysics 2012).

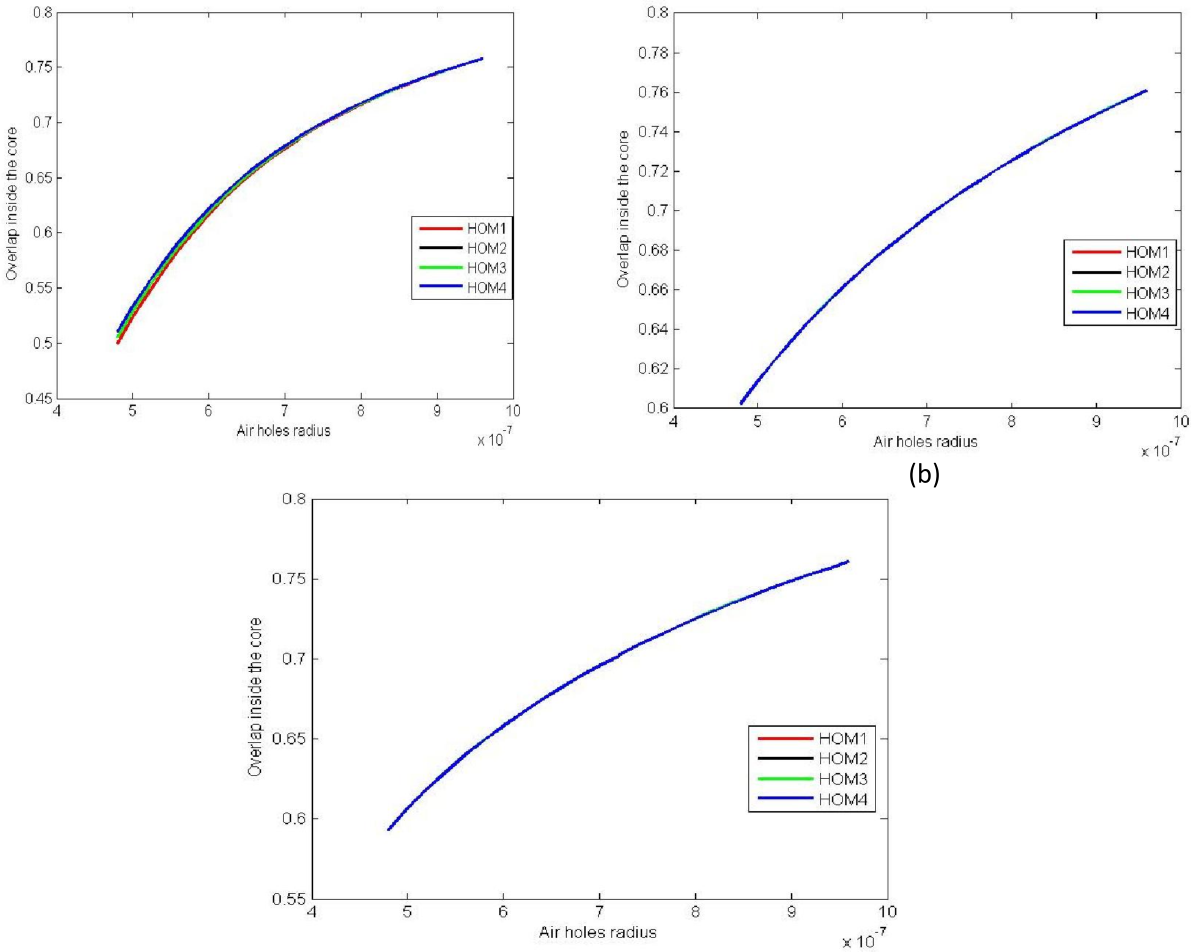
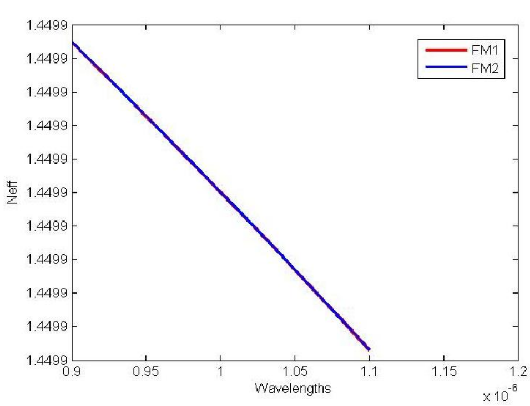


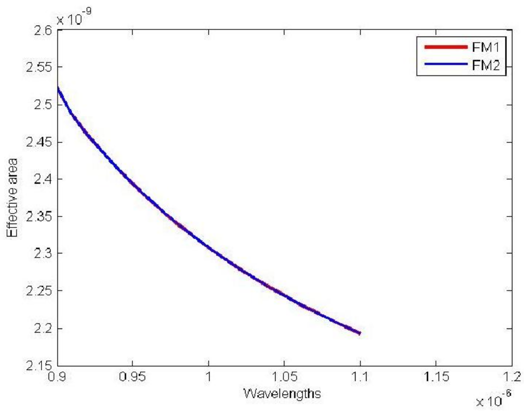
Fig.(4): The overlap integral of the Higher order Modes with respect to different air holes radius of the PCF with different air cladding radius (a) 72 µm (b) 83µm and (c) 87 µm

The effective index N_{eff}, effective area and overlap integral of the fundamental Modes are obtained for the 19 cell PCF with 3 rings, range of wavelengths= (900e-9 to 1100e-9), pitch=12 µm air cladding radius= 85 µm and air holes radius=0.72 µm, as shown in the Fig. (5)

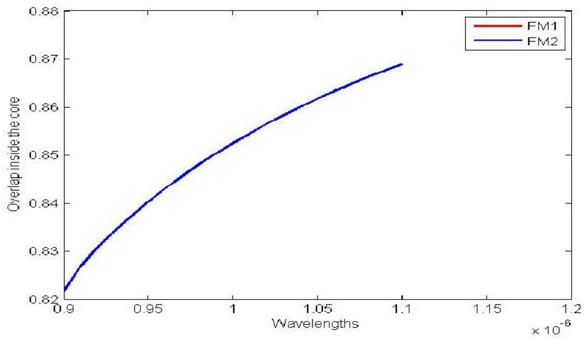
For the same design , the effective index and the overlap integral for higher order modes (HOM) are shown in the Fig.(6) .



(a)

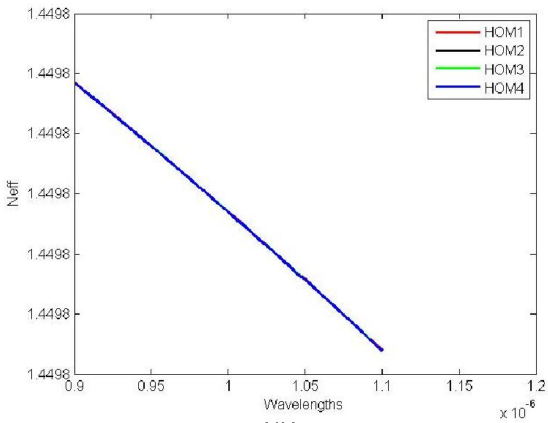


(b)

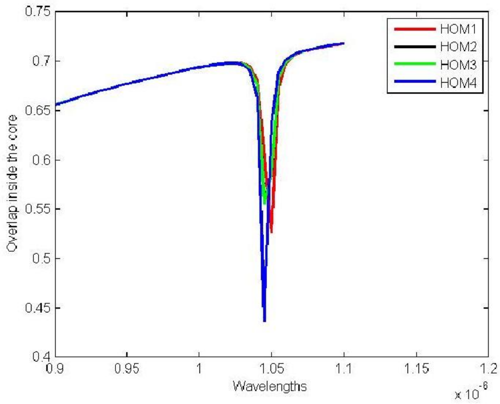


(c)

Fig.(5): (a) the effective index N_{eff} (b) effective area and (c) overlap integral of the fundamental Modes with respect to different wavelengths



(a)

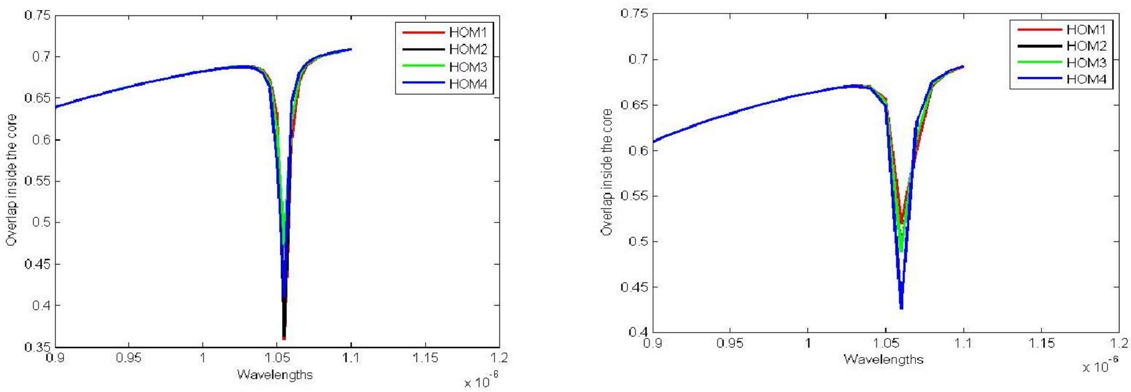


(b)

Fig.(6): (a) the effective index Neff and (b) overlap integral of the Higher order Modes with respect to different air holes radius of the PCF

By changing the air holes radius of the second and third rings with the first ring constant, the overlap integral of HOMs will be decreased for all ranges of the wavelengths

Fig (7). Shows the overlap integral of the higher order modes that are obtained for the 19 cell PCF with 3 rings, range of wavelengths= (900e-9 to 1100e-9), pitch=12 µm air cladding radius= 85 µm and air holes radius=0.72 µm with a) second and third air holes radius=0.60 µm b) and second and third air holes radius=0.48 µm



(a) (b)

Fig.(6):the overlap integral of the higher order modes for the 19 cell PCF with 3 ringsa) Second and third air holes radius=0.60 µm b)second and third air holes radius=0.48 µm

8. Conclusion.

The effect of ʌ/d and wavelengths on single mode operation for19-cell photonic crystal fibers with 3 rings in the fiber inner cladding is investigated with the avoided-crossing approach.. The single mode operation had been obtained by calculating the overlap integral of FMs and HOMs inside the core.It is found that the overlap integral is affected with changing the wavelength andʌ/d.For certain type of 19-cell photonic crystal fibers (i.e. certain of ʌ/d and wavelengths), the avoiding crossing had observed with HOMs but not with FMs. It means that we can get more loss for HOMs without affecting FMs if we use this type of 19-cell photonic crystal fibers with specific design of ʌ/d and wavelengths.

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