Iraqi J. Laser, Part B, Vol.12, pp. 37-42 (2013)

IRAQI
JOURNAL
OF
LASER

Chemical Sensor Based on a Hollow-Core Photonic Crystal Fiber

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(Received 24 February 2013; accepted 7 April 2013)

Abstract: In this work a chemical sensor was built by using Plane Wave Expansion (PWE) modeling technique by filling the core of 1550 hollow core photonic crystal fiber with chloroform that has different concentrations after being diluted with distilled water. The minimum photonic bandgap width is.0003 and .0005 rad/sec with 19 and 7 cells respectively and a concentration of chloroform that filled these two fibers is 75%.

Introduction

In recent years, new possibilities in developing chemical sensors for chemical biomedical research are offered by photonic crystal fibers [1].Hollow core photonic crystal fiber (HC-PCF) which guides light in a low index core such as air by coherent reflection from surroundings is called photonic bandgap (PBG) fiber. These PBG fibers can guide more than 98% of the light in the core and 2% in the silica cladding [2].

The core of PBG fiber has a defect which allows the existence of modes with certain frequencies that fall inside the PBG [3].

The periodic lattice surrounding hollow core determines the transmission windows of guided modes of PBG fibers [3].

The most general numerical methods which are used to simulate the full time- dependent Maxwell equationsto describe propagation of the fieldsin both time and space are finite difference time domain (FDTD)and Plane Wave Expansion (PWE) methods. These methods can be used to extract the modified bandgap of PBG fibers.[4].

The FDTD methodhas been represented in context to modal and polarization properties of the photonic designand PWE method has been represented in context to band gap analysis of the designedphotonic structure [4-6].

The FDTD modeling of photonic crystal waveguide in different materials is done by takingthe rectangular lattice waveguide structure and dielectric material of user defined constantrefractive index. The default material is taken to be air with unit refractive index and then infiltered with chloroform with different refractive indices according to varying the concentration of this organic material. The FDTDsimulation and analyses of modeled crystal gives the reflectance andtransmittance properties of the photonic band gap crystal and the electric and magnetic fieldcomponent for transverse electric polarization and the Poyntingvector also. The FDTD method has been established as a powerful engineering tool for integrated anddiffractive optics device simulations due to its unique combination of features, suchas the ability to model light propagation, scattering and diffraction, and reflection andpolarization effects [5-7].

Plane wave expansion method (PWE) refers to a computational technique in electromagnetics to solve the Maxwell's equations by formulating an eigenvalue problem out of the equation. This method is popular among the photonic crystal community as a method of solving for the band structure (dispersion relation) of specific photonic crystal geometries. PWE is traceable to the analytical formulations, and is useful in calculating modal solutions of Maxwell's equations over an inhomogeneous or periodic geometry [6].

Many research works focused for building chemical sensor based on infiltration of hollow core PCF with organic liquids like infiltration of 19 - cell hollow cores PCF with cholerogenum molecules with various concentration and study the variation of radiation field that propagates via it [1]. While other group research work focused on studying the laser diode modes overlap that radiated via 7 - cell photonic crystal fiber centered at 800 nm infiltered with five liquids that have variable concentrations, butanal, ethanol, hexane, methanol and propane .The laser modes are investigated by using Michelson interferometer[8]. In this work, the transmission and absorption spectra of chloroform were extracted using spectrophotometer with different concentrations, then cladding's photonic bandgap structure and photonic crystal states were calculated by using PWE method programmed in MATLAB for 19 and 7-cell photonic crystal fibers after and before infiltration with chloroform that have different concentrations.

Simulation Methods

Two - dimension photonic crystal lattices of the cladding of HC-PCF where first analyzed after fullysolvingthe vectorialeigenmodes of Maxwell's equations [9]. It is assumed that a change of refractive index is due to adding chloroform material inside air holes. The vector wave equation of Maxwell's equations in a linear, isotropic, and time-invariant medium is derived as:

$$\nabla \times \nabla \times \vec{E} = \nabla(\nabla \cdot \vec{E}) - \nabla^2 \vec{E} = n^2 k_0^2 \vec{E} \qquad (1)$$

Where n is the refractive index as a function of position, and $k_0 = 2\pi/\lambda_0$ is the wave number in free space. As therefractive index does that not vary along the z direction, the propagation of the electromagnetic wave is governed by twocoupled equations for E_x and E_y only. By writing the electric field as:

$$\vec{E} = (E_x \hat{x} + E_y \hat{y} + E_z \hat{z}) \exp(-j\beta z)$$

Where β is the propagation constant.

Considering only the transverse part of the field, an eigenvalue equation ofthis form can be obtained [10]

$$\begin{bmatrix} A_{xx} & A_{xy} \\ A_{yx} & A_{yy} \end{bmatrix} \cdot \begin{bmatrix} E_x \\ E_y \end{bmatrix} = \beta^2 \begin{bmatrix} E_x \\ E_y \end{bmatrix}$$

Standing waves of electromagnetic wavecan propagate through a periodic structure whose minimum features are less than thewavelength of light. In this case, the medium expels photons with certain wavelengths andwave vectors. Such a structure acts as an insulator of light, and this phenomenon is referredto as “photonic band gap”.

The two dimensional photonic band gaps structure has a hexagonal Brillouine zone, which has a radiation field zone that can be divided into symmetrical triangles and each triangle gives a full description of waves in a periodic medium .The Brillouine zone in Figure 1 is the triangle with vertices denoted by K,M and Γ. The eigen solutions for a triangular lattice of holes in a high refractive index material, TE and the TM band structures are shown too

This oval represents the region of lower and upper photonic band gap

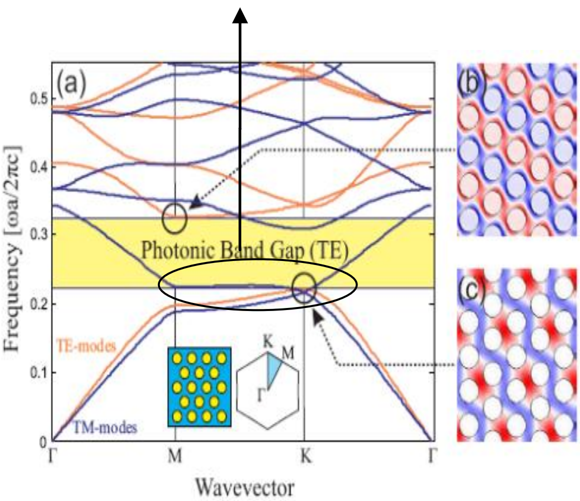

Fig. (1): The photonic band structure for a triangular lattice of holes in a high indexmaterial. (b) The magnet field pattern of the TE mode corresponding to thesecond band at the first M point. (c) The magnetic field pattern of the TE modecorresponding to the first band at the K point [11].

Results

Before filling the core of HC-PCF with chloroform. The transmission and absorption spectrums of this organic material as a function of concentration were recorded by using spectrophotometer as shown in Figures 2 and 3.

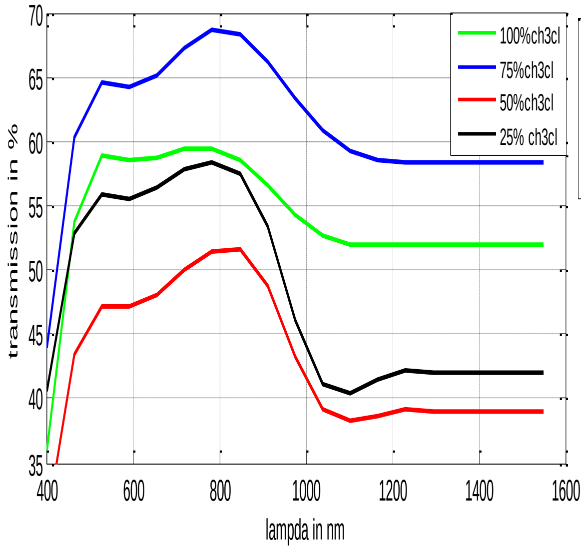

Fig. (2): The transmission spectrum of chloroform.

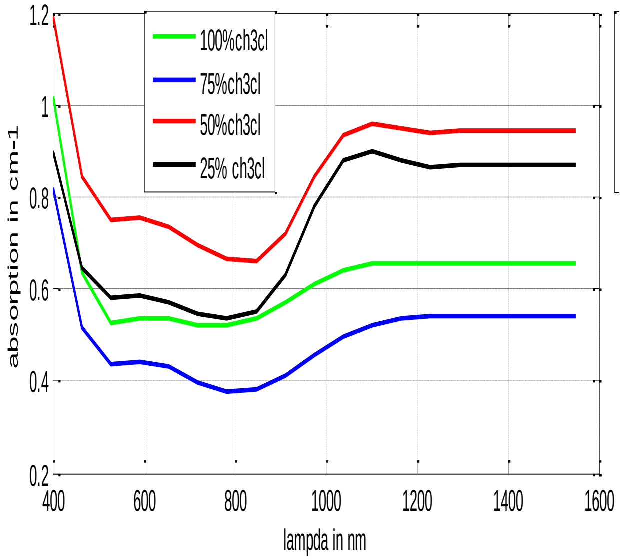

Fig. (3): The absorption spectrum of chloroform.

The band structure of HC19-1550 is shown in Figure 4, where the refractive index of air, n_a=1, and the refractive index of silica n_b=1.45, air filling fraction which is the lattice constant *f*= 90%, hole radius to lattice constant (r/Λ) =0.5, where Λ is the distance between two successive holes Photonic bandgap width is .0235 rad/s, and the complete band gap is between (0.5823-0.5588) rad/s which are referred as upper and lower normalized frequency band edges respectively as shown in Figure 4.

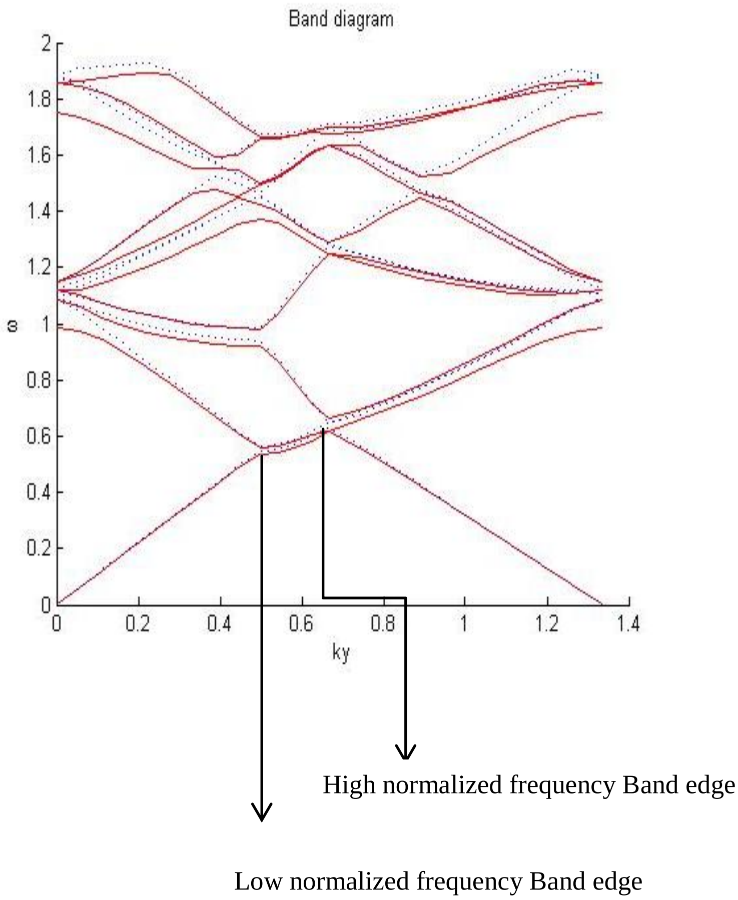

Fig. (4): Photonic band structure for HC19-1550 PC fiber.

After infiltration of the core of 19 - cell ,1550 nm, with chloroform with different concentrations, the photonic band structures and also the photonic bandgap width were extracted by using PWE method as demonstrated in Figures 5-8 and table (1) respectively where x – axis representsthe wavevector in the direction of mode propagation andy-axis represents the normalized angular frequency .

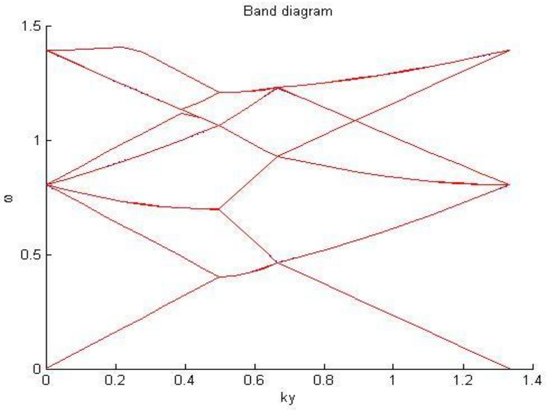

Fig. (5): Photonic band structure after 100% chloroform filling HC19-1550 PC fiber

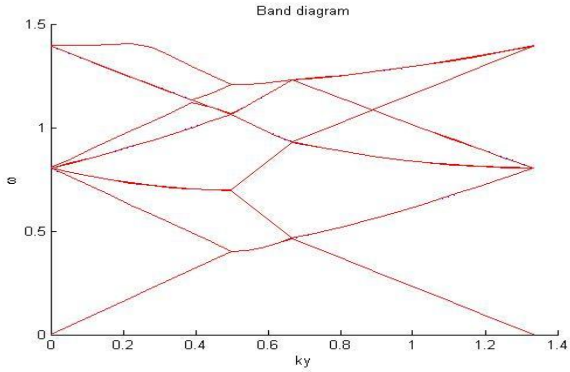

Fig. (6): Photonic band structure after 75% chloroform filling HC19-1550 PC fiber

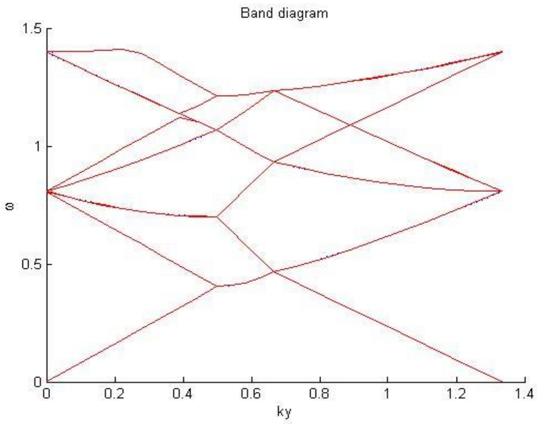

Fig. (7): Photonic band structure after 50% chloroform filling HC19-1550 PC fiber

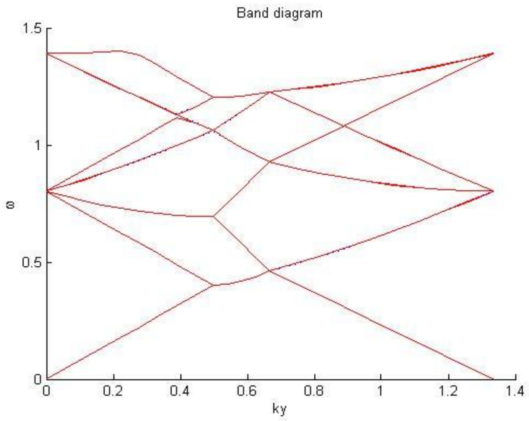

Fig. (8): Photonic band structure after 25% chloroform filling HC19-1550 PC fiber

Table (1): Photonic Bandgap width of chloroform infiltrated HC19-1550 PC fiber as a function of concentration

Concentrations	chloroform Refractive index ($n_{chloroform}$)	Low normalized Frequency Band edge	High normalized frequency Band edge	Photonic Bandgap Width (rad/sec.)
100% chloroform	1.4334	0.4063	0.4067	0.0004
75%chloroform&25% Distilled water	1.437	0.4054	0.4057	0.0003
50%chloroform&50% Distilled water	1.427	0.4079	0.4084	0.0005
25%chloroform&75% Distilled water	1.432	0.4067	0.4071	0.0004

The same procedure was repeated to find thebandgap width of HC7-1550 that was demonstrated before and after filling with chloroform with different concentration where n_a=1 and n_b=1.45, *f*= 90%, r/Λ=0.4780 . Photonic bandgap width is .048 rad/s and the complete band gap between (0.579 - 0.531) rad/s as shown in Figure 9.

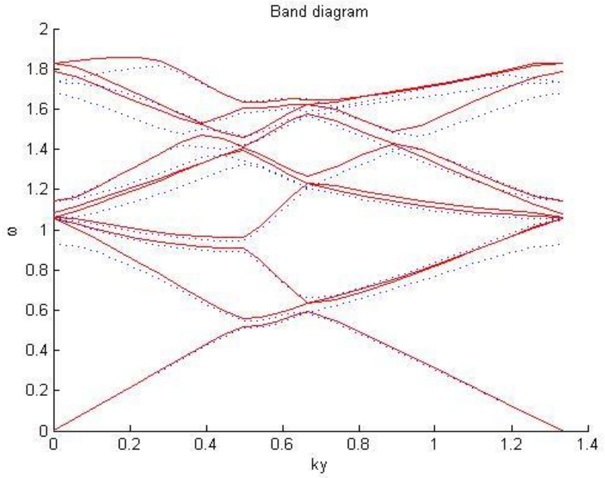

Fig. (9): Photonic band structure for HC7-1550 PC fiber.

But, when infiltration the core of 7 – cell, 1550 nm, with chloroform as a function of concentration the photonic band structures and also the photonic bandgap widths were extracted asdemonstrated in Figures 10-13 and table (2) respectively.

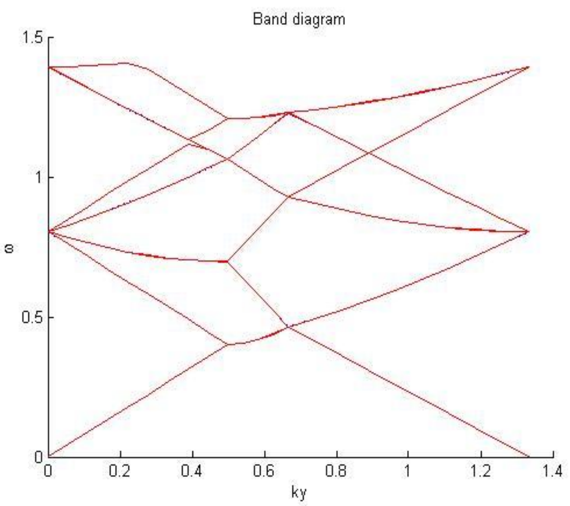

Fig. (10): Photonic band structure after 100% chloroform filling HC7-1550 PC fiber

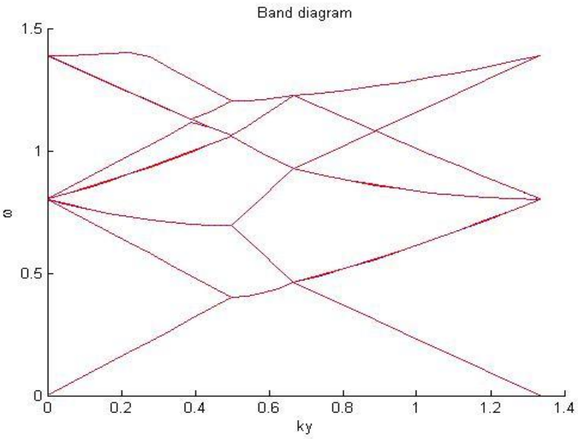

Fig. (11): Photonic band structure after 75% chloroform filling HC7-1550 PC fiber

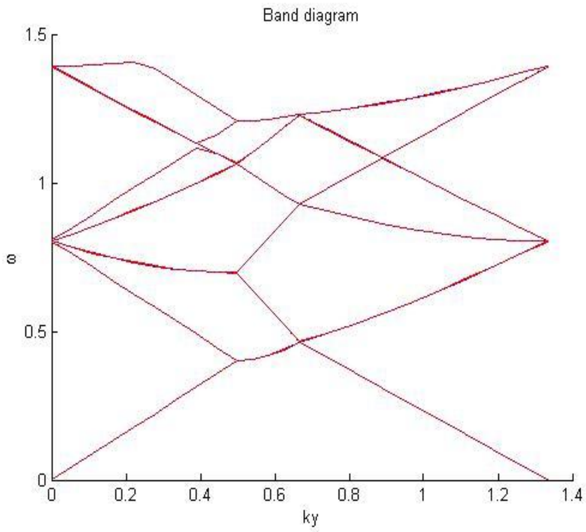

Fig. (12): Photonic band structure after 50% chloroform filling HC7-1550 PC fiber

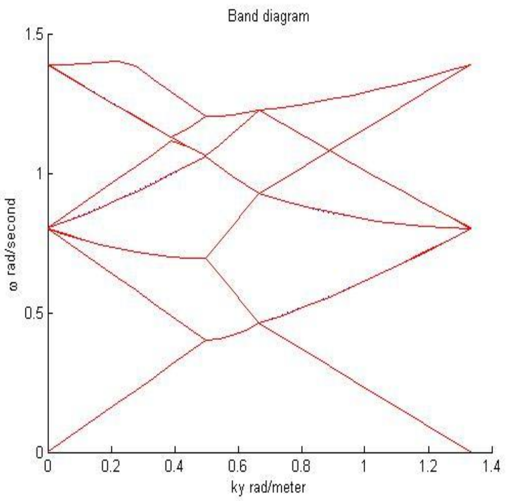

Fig. (13): Photonic band structure after 25% chloroform filling HC7-1550 PC fiber

Table (2): Photonic Bandgap width of chloroform infiltrated HC7-1550 PC fiber as a function concentration.

Concentration	chloroform Refractive index ($n_{chloroform}$)	Low normalized Frequency Band edge	High normalized frequency Band edge	photonic Bandgap Width (rad/sec.)
100% chloroform	1.4334	0.4058	0.4065	0.0007
75%chloroform&25% Distilled water	1.437	0.4051	0.4056	0.0005
50%chloroform&50% Distilled water	1.427	0.4072	0.4081	0.0009
25%chloroform&75% Distilled water	1.432	0.4061	0.4068	0.0007

Conclusions

Before infiltrationof the core of the hollow core photonic crystal fiber it can be shown that the transmission is indirectly proportional with concentration but at 50% concentration the transmission will decrease while the absorption is directly proportional with concentration. After infiltration with this organic material, chloroform, the low and high normalized frequencies are decreased that are indirectly proportional with concentration of this material that filled these two fibers except at the point where the concentration of the material is about 50%. When compared with the same concentration of chloroform but first with 19 - cell and then with 7 - cell PCF it can be shown that the photonic bandgap width for 19- cell PCF is larger than the bandgap width of 7-cell PCF.

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بناء متحسس كيميائي باستعمال ليف بصري بلوري ذو قلب هوائي

تحرير صفاء منصور   داليا حسين عباس

معهد الليزر للدراسات العليا ، جامعة بغداد ، بغداد ، العراق
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الخلاصة: في هذا العمل تم بناء متحسس كيميائي باستعمال نموذج والذي هو تقنية توسيع المجال الموجة لليف البصري البلوري ذو الفجوة الهوائية لطول موجي 1550 وب 19 و7 خلية محذوفة بعد حقنه بمادة الكلورم المخففة التركيز باستعمال الماء المقطر. وقد حصلنا على . 0003.و 0005. فجوة الحزمة الفوتونية عندما كان تركيز الكلوروفورم 75% في كلتا الحالتين.