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The Impact of MEH-PPV Organic Thin Film on the Emission and the Q-Factor of L3 Nanocavities

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Abstract

In this paper, the influence of removing three holes called L3 nanocavities to achieve a high quality factor (Q-factor) of two-dimensional photonic crystal (2D-PC) and its optical properties were investigated. There are two important factors that are modified to obtain a high quality factor, which are changing the hole size, and after that, hole shifting. Next, the effect of organic-semiconductor materials on the cavity photoluminescence (PL) photonic crystal (PC) was studied. Fabrication techniques to create the photonic crystal L3 nano-cavity are described. In addition, the impact of the deposited organic-semiconductor emitter spectrum on the electromagnetic field intensity within the L3 nanocavity was measured using photoluminescence spectroscopy. Finally, the hole size of the (2D-PC) nanocavities and its lattice constant were characterized utilizing scanning electron microscope (SEM).

Keywords: photonic crystal, organic-semiconductor, quality factor (Q-factor)

تأثير الغشاء الرقيق العضوي MEH-PPV على انبعاث تجاويف النانو L3

فالح لفته مطر الجشعمي[1]

قسم الفيزياء ، كلية العلوم ، جامعة تكريت ، تكريت ، العراق

الخلاصة

في هذه الورقة، تم التحقيق في تأثير إزالة ثلاثة ثقوب تسمى تجاويف النانو L3 لتحقيق عامل جودة عالي (عامل-Q) للبلورة الفوتونية ثنائية الأبعاد (2D-PC) وخصائصها البصرية. هناك عاملان مهمان يتم تعديلهما للحصول على عامل جودة عالي، وهما تغيير حجم الفتحة، وبعد ذلك، إزاحة الفتحة. بعد ذلك، تمت دراسة تأثير المواد شبه الموصلة العضوية على البلورة الفوتونية الضوئية (PL) للتجويف. تم وصف تقنيات التصنيع لإنشاء تجويف النانو L3 للبلورة الفوتونية. بالإضافة إلى ذلك، تم قياس تأثير طيف باعث أشباه الموصلات العضوية المترسب على شدة المجال الكهرومغناطيسي داخل تجويف النانو L3 باستخدام مطيافية الضوئية. أخيرًا، تم توصيف حجم الفتحة في تجاويف النانو (2D-PC) وثابت الشبكة الخاص بها باستخدام المجهر الإلكتروني الماسح (SEM) .

1. Introduction

Periodic optical structures with layers of varying refractive indices which affect the propagation of electromagnetic waves are known as photonic crystals (PC) [1-4]. The production of nanocavities is possible by the introduction of defects inside a photonic crystal, one or more missing holes, having a photonic band-gap. They are called an optical nanocavity because they have the ability to confine light within volumes that are smaller than a cubic wavelength (λ/n)3. The optical field can be strongly localized as a result of the formation of very high-quality factors from such structures. [5-9]. Nanocavity structures are useful as single photon devices working at visible wavelengths [10].

First mentioning the banned stop-band in one dimensional periodic medium in 1887 was the Lord Rayleigh. [11]. The photonic band gap then became of interest to researchers studying photonic crystals, in order to confine light within periodic nanostructure in a wavelength size using the principle of total internal reflection (TIR) and reflection due to periodic dielectric [12-27]. Light propagation in dielectric media is governed by Maxwell's macroscopic equations [28].

$$\nabla . \vec{\mathrm{B}} = 0 \tag{1}$$

$$\nabla . \vec{D} = \rho \tag{2}$$

$$\nabla \times E + \frac{\partial \vec{B}}{\partial t} = 0 \tag{3}$$

$$\nabla \times \vec{H} - \frac{\partial \vec{\mathrm{D}}}{\partial \mathrm{t}} = \vec{\mathrm{J}} \tag{4}$$

E is referring to the electric field, while the symbol H is referring to the magnetic field, also the symbol B is referring to the magnetic flux density, as well the symbol D is referring to the electric displacement, additionally the symbol J is referring to the electric current density, and finally the symbol ρ is referring to the electric charge density [29]. When light propagates through a mixed dielectric media without any light sources present, it is possible to consider $\rho = 0$ and $J = 0$ [30]. The definition of the auxiliary fields is as follows:

$$\mathrm{D} = \mathrm{E} + 4\pi \mathrm{P} \tag{5}$$

$$\mathrm{H} = \mathrm{B} - 4\pi \mathrm{M} \tag{6}$$

$$\mathrm{P} = \overleftrightarrow{\chi}_e \, . \ \mathrm{E} \tag{7}$$

$$\mathrm{M} = \overleftrightarrow{\chi}_m \, . \ \mathrm{H} \tag{8}$$

P is referring to the "polarization field, as well the symbol M is referring to the "magnetization field and at last the symbol χ is referring to the electric and the magnetic susceptibility [31].

There is a limited number of light frequencies which are unqualified to propagate through a periodic dielectric material. This phenomenon is referred to as a photonic band gap. Dielectric materials usually refer to the kind of materials that are poor conductors of electricity and not used to transfer electrical energy through conduction. Such materials possess many useful properties, including piezoelectricity, nonlinearity, and photosensitivity [32]. It is worth noting that photonic nanostructures enable the achievement of light to be confined within a small volume of 2D nanocavity, for a comparatively long photon lifetime. Strong photon localization in nanocavities has resulted in highly significant and innovative applications in nonlinear optics and quantum. Memory elements, low-power optical switches, in addition to zero-threshold lasers are some examples of these applications [33-34].

Here, the dielectric material utilized was silicon nitride, which having a small photonic bandgap and a refractive index of 2.0. Due to the advantageous properties of the silicon nitride, including the large variation between the oxide shell ($n \approx 0.5$), In addition to this important feature, which is a large refractive index, this led to the light being effective and helping in high-density integration. [35].

Organic materials have attracted significant interest for applications in photonics as a result of their large nonlinearity, fast response speed [36-37], linked by van-der-Waals bonded have considerably less intermolecular interactions relative to covalently linked semiconductors like Si [38], absorb light in a layer just 100 nm in thickness [39], conduct electricity [40], ease fabrication [41], and have very low optical loss [42]. In a conjugated molecule, electrons and holes are situated in the (HOMO) which is the highest occupied molecular orbital in the organic semiconductor, and many of these materials exhibit excellent photoluminescence (PL) efficiency and low toxicity. After light is absorbed in organic semiconductor, excitons may be produced during the electronic transition between a single molecule's LUMO and HOMO [43].

2. Experimental Techniques

The substrate that was used was made from a SiN membrane having a refractive index of 2.1 and thickness of 200 nm. The membrane was purchased from Silson Ltd. The standard procedure used to process the photonic crystal samples is:

1- To get rid any moisture, hot plate was used to baked the substrate for one minute at 100^{o} Celsius.

2- A PMMA, (polymethyl methacrylate) photoresist was spin-cast on the SiN membrane at speed of 4000 rpm for 30 seconds, creating a 200 nm thick PMMA layer..

3- Hot plate was utilized again to solidify the resist by evaporating the solvent for 10 minutes.

4- The photoresist was subjected to the electron beam irradiation.

5- The exposed photoresist was developed with methyl isobutyl ketone and isopropanol in specific ratios of MIBK: IPA, 1:3, and alcohol, for 30 seconds at 23^{o}C and then rinsed in IPA for 10 seconds followed by a blow-dry by nitrogen gas. As there is a good selectivity between the PMMA and the SiN in a fluorine based reactive ion etching (RIE) system, the PMMA was used as an etch mask for the SiN membrane.

6- RIE (reactive ion etching) was used to remove both the uncoated SiN. Etching parameters as pressure, RF power, the gas type and flow rates need to be carefully chosen. A typical etch time of 10 minutes was required to etch 200 nm deep holes in SiN.

7- The remaining PMMA mask was then removed utilizing an oxygen plasma asher for 10 m, creating the photonic structure as illustrated in figure 1.

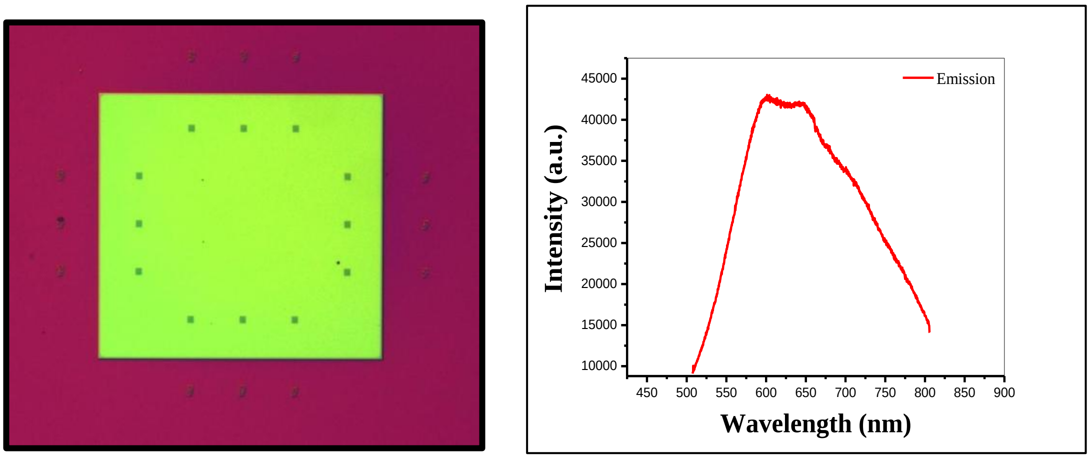
8- Far field optical spectroscopy was utilized to measure photoluminescence emitted from the photonic crystal nano-cavities.

9- MEH-PPV organic material coated onto the photonic crystal nanocavities.

10- Figure 2 illustrate the emission spectra and the chemical structure for the different organic materials such as Red-Lumogen, P3HT and MEH-PPV.

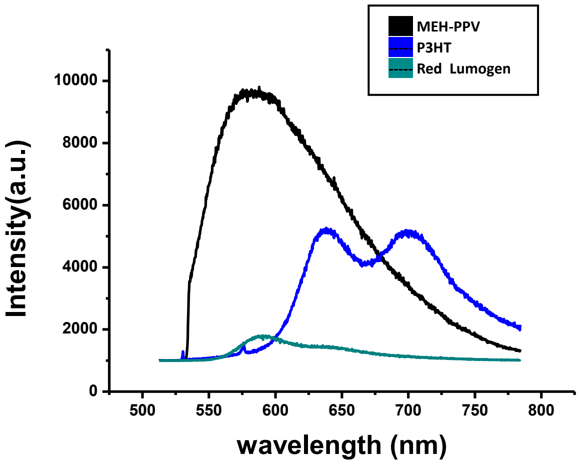
In this work, MEH-PPV was chosen because its emission spectrum was suitable to the photoluminescence (PL) emission of SiN and the second reason is that its emission intensity is high compared to the other two organic materials.

11- Finally, SEM was utilized to image the photonic crystal as shown in figure 4, allowing us to compare it with the theoretical measurements as in figure 3.

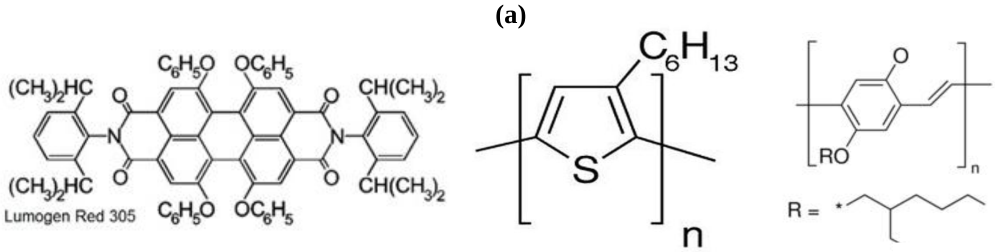


(a) **(b)**

Figure- 1 Illustrates (a) the SiN membrane window fabricated that contains 12 PC structures (b) the PL emission of SiN.



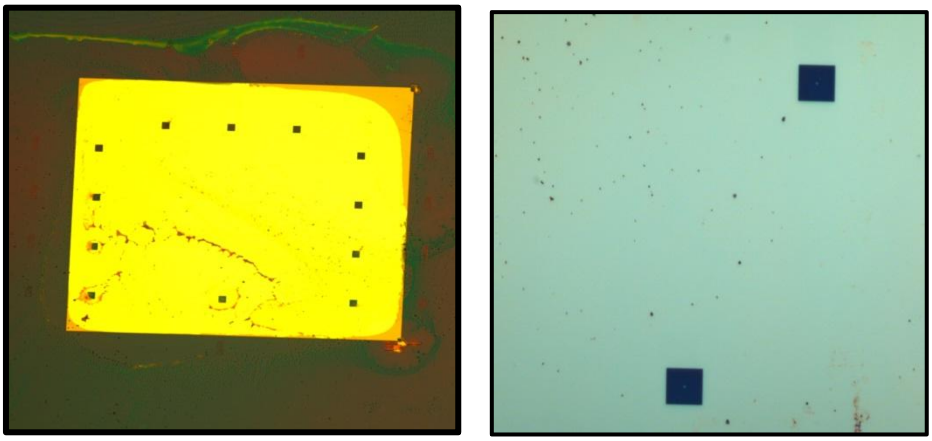
(a)



(b) **(c)** **(d)**

Figure- 2 Shows (a) the emission spectra and (b-c-d) the chemical structure for Lumogen Red, P3HT and MEH-PPV organic materials respectively.

The SiN membrane windows after coating with MEH-PPV is illustrated in figure 3.



(a) **(b)**

Figure- 3 Shows: (a) SiN membrane windows after coating with MEH-PPV.
(b) Two photonic crystals after coating with MEH-PPV.

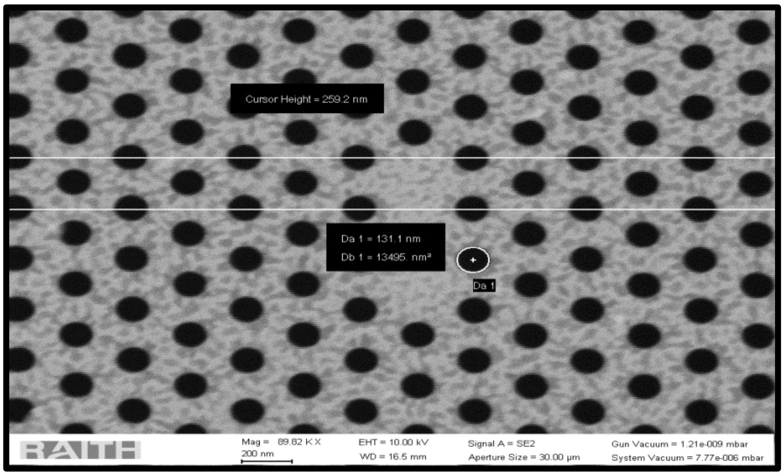


Figure-4 Shows the SEM for nanocavity fabricated in this work

3. Results

3.1 Design L3 cavity two-dimension photonic crystal

3.1.1 Hole size effect

It has been investigated how the hole size affects an L3 nanocavity's optical mode. With a membrane thickness of 200 nm and a lattice constant of 260 nm, a triangular lattice shape was employed. The hole's diameter was expanded to 180 nm from 120 nm as shown in figure 5. The luminescence in the nanocavities came from the intrinsic luminescence of SiN that is enhanced by the cavities. Here it should be noted that with the change in the hole size and hole location the leakage of optical modes decreases.

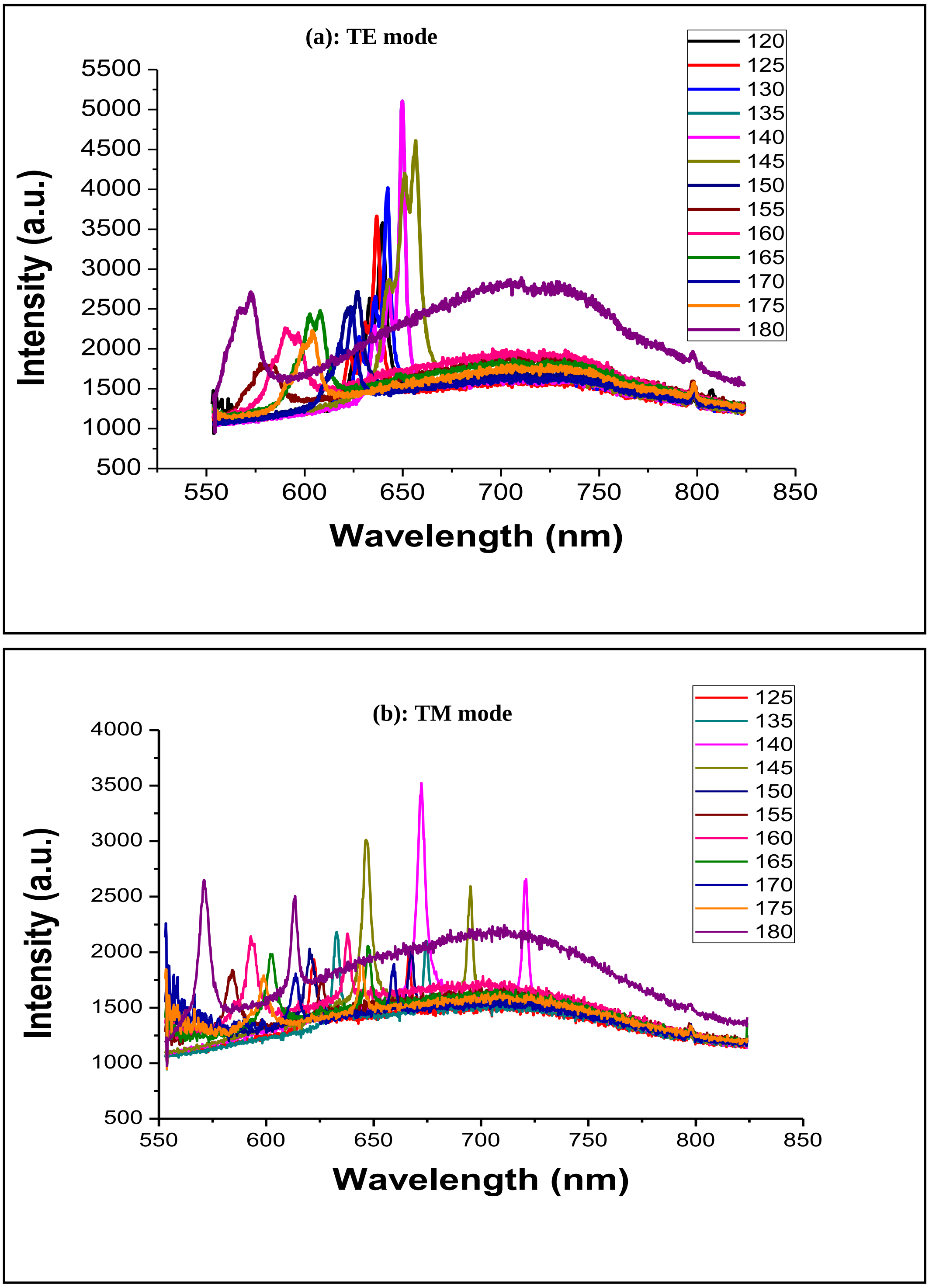
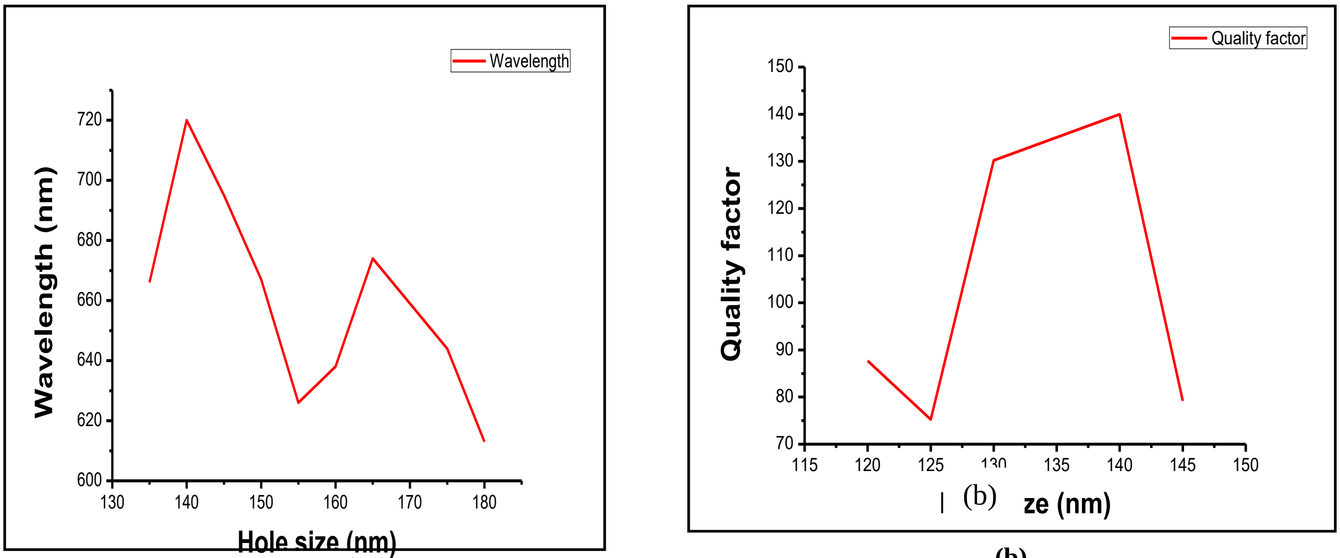


Figure- 5 (a) and (b) Show the spectrum taken from various hole size (nm) nanocavities for both TE and TM mode respectively

Here, as the hole size expands, the cavity mode wavelength becomes more sensitive to it and moves to higher frequencies in most photonic crystals, as illustrated in figure 6(a). A high Q factor cavity depends on the amount of losses from the cavity as a result of scattering from the optical mode into the nanocavity. We find the quality factor is maximized for hole size 140 for TE modes as illustrated in figure 6(b).



(a) **(b)**

Figure-6 Shows (a) The hole size is shifted from low to high frequency as hole size expands
(b) The change of quality factor as relating to the hole size for TE modes.

Spin-casting has been used to deposit MEH-PPV organic materials on top of the PC nanocavities to see the effect of the optical modes on the organic excitons. Organic semiconductors solution was prepared by dissolving MEH-PPV in toluene at a concentration of 0.5 mg/ml. Producing thin films with a thickness of 10 nanometres, spin coating technique was utilized at a speed of 2000 rpm for 1 minute.

Figure 7 below illustrates the photoluminescence spectrum of a thin film of MEH-PPV coated on a two-dimensional photonic crystal nanocavity. This emission is the consequence of the PL from the MEH-PPV thin film overlapping with the emission from the cavity which is enhanced. The quality factor is increased 1.5 times from 140 to 210 practically. Mathematically, the value of the quality factor can be calculated using the following equation:

$$Q = \lambda/\Delta\lambda \tag{9}$$

λ is referring to the central wavelength of the resonance, as well the symbol $\Delta\lambda$ is referring to the (FWHM) which is the full-width half-maximum value of the resonance [44].

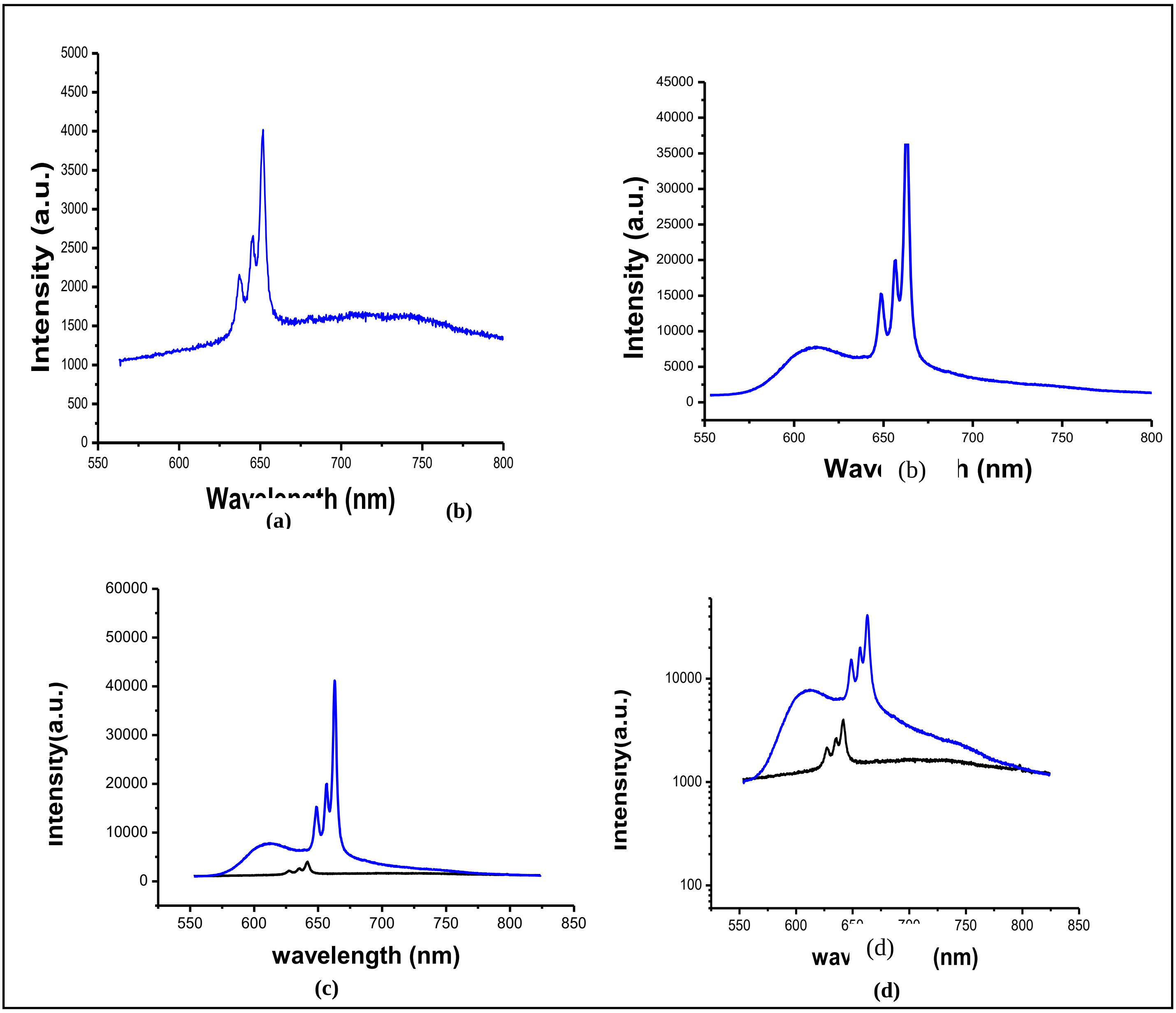
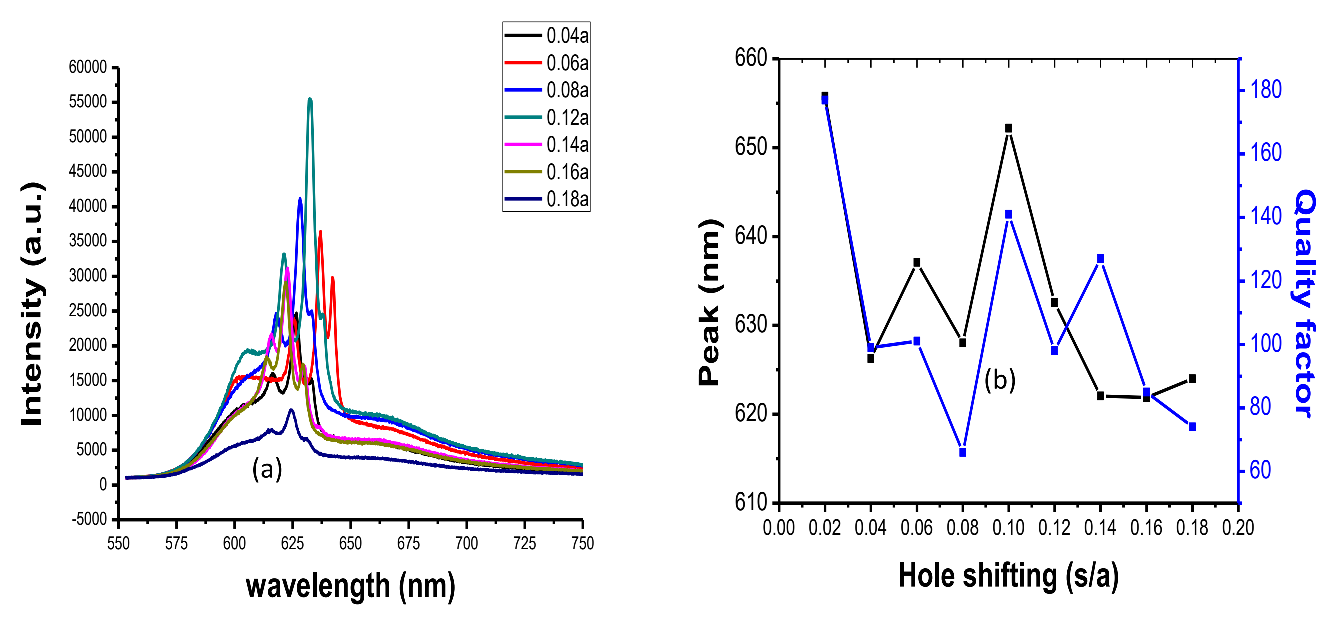


Figure -7 Shows the cavity with hole size 140 nm, a-before coating with MEH-PPV, b- after coating with MEH-PPV , c- illustrates the emission from the cavity before and after coating in linear scale and d- illustrates the emission from the cavity before and after coating in log scale

Higher quality factor cavities can be achieved by reducing the energy losses per cycle. Quality factor depends on reflection losses at the air-material interface. Confining light inside the cavity was achieved by Bragg reflections and total internal reflection between the air cladding and SiN membrane interface. The escape modes depend on their direction along the cavity axis. Therefore, any change in the location of the surrounding cavity holes effects on the leaky optical modes. Engineering the position of side holes can increase optical confinement and increase Q factor [44]. To explore this effect, L3 cavity holes on the long axis were shifted by the ratio of s/a from 0.02 to 0.18, where s is hole size and a is the lattice constant. The change in the peak fundamental mode resonance wavelength and quality factor value was measured for TM and TE polarization as shown in figure 8, in which the quality factor reached 136 before coating with MEH-PPV.



(a) **(b)**

Figure- 8 (a) TE Fluorescence emission as relating to the shift of holes s/a.
(b) Demonstrates the change of the wavelength and quality factor with the hole shifting

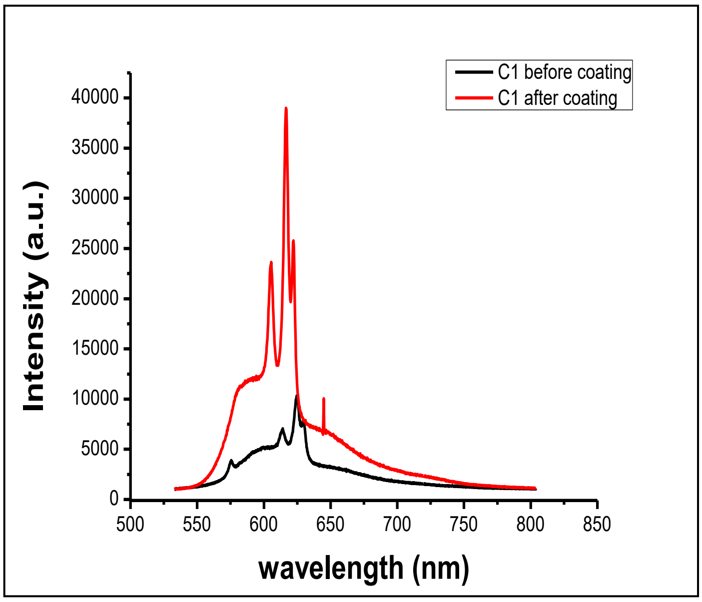
The change in the peak mode resonance and quality factor value was determined for the TE mode before coating with organic material, as shown in table 1.

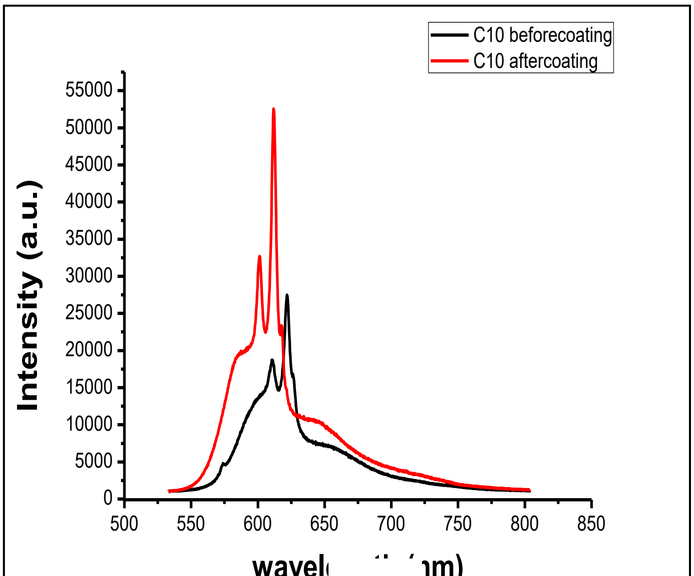
Table 1- Illustrates the change of quality factor according to hole shifts.

Shift(s/a) (nm)	**Peak (nm)**	**Quality factor**
0.02	655.8	177
0.04	626.26	99
0.06	637.1	101
0.08	628.02	66
0.1	652.18	141
0.12	632.57	98
0.14	622.06	127
0.16	621.89	85
0.18	623.99	74

3.1.2 Hole shifting effect after coating with HEH-PPV organic material

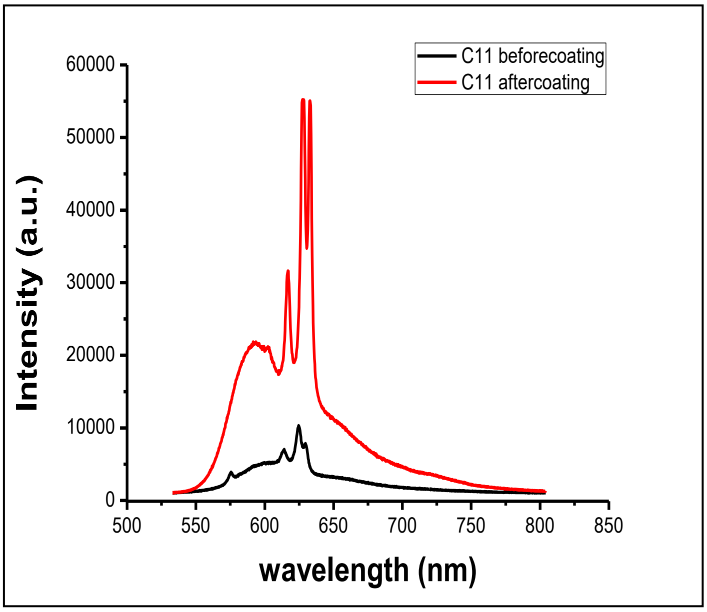
Figure 9 below illustrates the fluorescence emission spectrum of a thin film of MEH-PPV coated on nanocavities. Here, the best three cavities of two-dimension photonic crystal were illustrated. The emission from the cavity fundamentally is caused by the overlapping with the luminescence from thin film of MEH-PPV which leads to enhance the emission of the cavity. The Quality factors of the coated cavities increased from 101 to 174, 98 to 365 and 141 to 175 for the cavities C1 which is s/a=0.06, C10 is s/a=0.1 and C11 s/a=0.12 respectively.





(b)

(a) (b)



(c)

Figure-9 Shows the hole shifting effect on three photonic crystal cavities before coating in the black line and after coating with 10^{-1} of Lumogen Red in the red line, a- s/a=0.06, b- s/a=0.1 and c- s/a= 0.12

This emission is the consequence of the PL emitted from the thin film of MEH-PPV overlapping with the emission from the nanocavity mode wavelength that leads to enhance the emission of the film. The enhancement was resulted from; the presence of the organic material causes the surface to become relatively flatter; the decrease in excitation power required for spectral collection from the organic-coated cavities is attributed to the substantial increase in oscillator strength and improved fluorescence quantum efficiency of the organic materials. to the SiN. Here, the quality factor increased 3.7 times to 365 as shown in table 2, which are considered the best three samples were obtained.

Table 2- Illustrates the change of quality factor according to hole shifts.

The sample	Hole shifting	Quality factor without organic material	Quality factor after using MEH-PPV
C1	0.6a	101	174
C10	0.1a	98	365
C11	0.12a	141	175

4. Conclusion

The optical properties of two-dimensional structure of photonic crystal nanocavities and the effect of organic-semiconductor materials on the cavity photoluminescence (PL) photonic crystal (PC) were studied. The impact of hole size of two-dimensional photonic crystal of lattice constant 260 nm was studied. A shift towards higher frequencies is observed as the hole size increases. For 140 nm hole size and a=260nm, the Q factor reached 140. However, a Q factor of order 210 was achieved by adding MEH-PPV thin film to the cavity surface. Moreover, the impact of shifting the holes on the quality factors was clear, with quality increased to 365 after using MEH-PPV organic material with shifting ratio s/a=0.1. The high Q-factors obtained in most of the nanocavities studied suggest great potential for further work. Nanocavities with a high Q-factor that incorporates organic materials will be of considerable importance for the development of various devices, including high-efficiency organic nanoscale light sources and integrated nanoscale organic lasers. The important effect which needs to be studied is the possible enhance in the overall spontaneous emission rate of an organic material deposited on the nanocavity surface. Organic material thin film with narrow emission linewidth is of interest to researchers and needs to be precisely deposited on the cavity surface within a range that corresponds to the maximum optical mode field.

Disclosure and conflict of interest

"Conflict of Interest: The authors declare that they have no conflicts of interest."

5. References

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