Inhibited and Enhanced Spontaneous Emission from Quantum Dots using 2D Silicon-Based Photonic Crystal Waveguides

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Abstract

Inhibited and enhanced spontaneous emission of light is essential to quantum optics in design and development of high efficiency optical devices which are useful for security optical communication systems and for diverse applications such as Optical Time-Division-Multiplexing (OTDM), Optical Switch, Super Lens, Negative Refractive Index, Laser, LED, and Single Photon Source (SPS). The triangular lattice and square lattice have been proposed for a security optical communication system. However, these simulations and experiments faces many obstacles. Thus, we developed an efficient single photon source by controlling inhibited or enhanced spontaneous emission of the photon using a two-dimensional silicon-based honeycomb lattice patterned photonic crystal waveguide. A quantum dot embedded in the planar photonic crystal membrane waveguide is the light source. The honeycomb lattice of circular air holes on a silicon plate is simulated to obtain large completely photonic band gaps. This significant property shows the potential applied guide modes of a photonic crystal membrane for controlling inhibited or enhanced spontaneous emission between the quantum dots and the photonic crystal waveguide. Significantly, this work is oriented to produce novel single photon sources which can emit one photon at a time for a quantum optical security network with single photon state. In addition, the honeycomb lattice can easily be made on a Si on insulator (SOI) wafer.

Keywords: Inhibition and enhancement, Spontaneous emission, Single photon source, Photonic crystal waveguide, Honeycomb lattice, Optical network security, Quantum key distribution

1. Introduction

Recently, quantum information technology has received considerable attention from the research community and industrial sectors in various fields such as security and communications. Apart from those attenuated classical Poisson-distributed sources demand on development of light sources whose photon number is able to be carefully controlled with high efficiency. In other words, research attempts are to implement a single-photon source that is capable of avoiding multiple-photon generation for continuing transmission mode. Its uses encompass various applications ranging from quantum cryptography, communications and computation. In a quantum system, single-photon state define bits which are technically called Qubits. Under the no-cloning theorem those quantum bits are not allowed to be duplicated without disturbing the system, i.e. noticed by the receiver side [1]. Several approaches have been invented and proposed in the literature including laser excitation sources and single quantized systems, such as:an atom, an ion, molecules, single quantum dots, and single nitrogen vacancy color centers in bulk diamond [2]. Self assembly quantum dots can be easily grown by Molecular Beam Epitaxial (MBE), and are then embedded in microcavity (point defects) or waveguide (linear defect) of a photonic crystal [3]. In 1887 L. Rayleigh proposed a technique that can control spontaneous emission based on Photonic Band Gap (PBG) in a one-dimensional slab (1D PhC) [4]. In 1946, E.M. Purcell predicted a spontaneous emission property of a quantum dot embedded in a microcavity [5-6]. In 1987, E. Yalonovitch and S. John showed a two-dimensional photonic crystal (2D PhC) [4]. In 1995, J. D. Joannopoulos proposed a honeycomb lattice three-dimensional photonic crystal (3D PhC), which has a complete photonic band gap and a simpler fabrication than triangular lattice-based one [7]. These lead to a conclusion that the inhibited or enhanced spontaneous emission of a single photon is controlled successfully by the photonic crystal. Moreover, from theory and experiments, photonic crystal structures of both the square lattice and the triangular lattice geometry were proposed [8].

In this paper, we propose two-dimensional photonic crystal waveguides of the honeycomb lattice in order to modify and control spontaneous emission from a quantum dot. In addition, from our study the proposed method can be applied to creation of an efficient single photon source.

The paper is organized as follows. Section II presents the two-dimensional honeycomb lattice geometric, photonic band structure, photonic crystal waveguide, guided modes and quantum dots. The photonic band structure, guided modes and density of states of the honeycomb lattice waveguide are simulated by Plane Wave Expansion Method (PWEM) in Section III. Finally, conclusion and future work are presented in Section IV.

2. Methods and Models

Photonic crystal waveguides of both the square lattice and the triangular lattice have been developed for controlling the spontaneous emission property from single quantized systems. Next, the two-dimensional honeycomb lattice geometry has been improved from both analysis and experiment [9]. Properties have been controlled very suitably to modify and to control the spontaneous photon emission property. Based on the fact that a two-dimensional honeycomb lattice features a larger complete photonic band gap and easier fabrication compared to those of the triangular lattice [10] we offer a two-dimensional photonic crystal waveguide with honeycomb lattice whose unit cell is similar to the atomic structure of graphite as shown in Fig. 1(a). In this design, we use a silicon material slab drilled into the circular air hole as shown in Fig. 1(b). In this case The honeycomb patterned photonic crystal membrane has primitive lattice vectors a_i,

$$\alpha_1 = \frac{\alpha\sqrt{3}}{2}(1,\sqrt{3}) \qquad (1)$$

$$\alpha_2 = \frac{\alpha\sqrt{3}}{2}(-1,\sqrt{3}) \qquad (2)$$

where α is lattice constant of the 2D honeycomb lattice structure as shown in Fig. 1(c) and is delimited by the three symmetry points are Γ, M and K, respectively, whose wave vectors (k) are in its first Brillouin zone. This honeycomb lattice is used to create the optical devices, e. g. telecommunication wavelength. Considerable parameters include the radius (r), thickness (d), dielectric constant (ε) and lattice constant (a). In the numerical study we adopt the PWEM and super-cells approach for calculations the photonic band gap, density of state (DOS), guided modes and display mode profiles through the available free software MIT Photonic Bands (MPB) package [11].

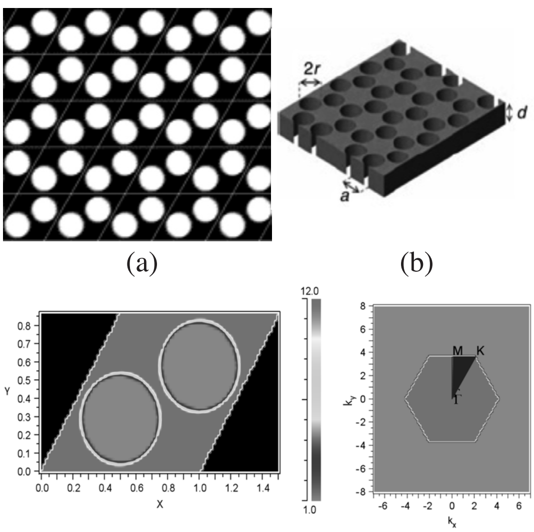


Fig. 1. Photonic crystal structures of the honeycomb lattice (a) Inside one unit cells has two circular air holes (b) the silicon material slab drilled into the circular air holes [12] (c) dielectric constant profile at z=0, primitive lattice vectors a_i and (d) Brillion zone and Kpath.

Photonic Band Structure

Previously, the photonic band structure of both the square lattice and the triangular lattice in TM mode has been presented [8-10]. In designing the photonic band structure, the parameters have been optimized to control the spontaneous emission [11-12]. We studied the two-dimensional photonic crystal membrane. The dielectric structure in the z-direction is uniform silicon material and in the x-y plane is periodic between silicon with air holes. We consider a periodic structure defined by a position dependent dielectric constant ε(r). The magnetic field H(r) or transverse magnetic modes (TM mode) and electric field E(r) or transverse electric modes (TE mode) are satisfied by the following master equation respectively.

$$\nabla \times \left[\frac{1}{\varepsilon(r)} \nabla \times H(r) \right] = \frac{\omega^2}{c^2} H(r) \qquad (3)$$

$$\frac{1}{\varepsilon(r)} \left[\nabla \times \nabla \times E(r) \right] = \frac{\omega^2}{c^2} E(r) \qquad (4)$$

where c is the light velocity in vacuum and ω is the angular frequency. To solve master equations (3) and (4), we expand the plane waves of fields H(r), E(r) and inverse dielectric function $\varepsilon^{-1}(r)$ in series of plane waves for a given wave vector (k) in the Brillouin zone as in equation (5):

$$\frac{1}{\varepsilon(r)} = \Sigma\, \kappa(G) e^{iG.r} \qquad (5)$$

where G is the reciprocal lattice vector and κ(G) is the Fourier transform of the inverse of dielectric function ε(r). Corresponding to Bloch's theorem, we only have to consider wave vector (k) inside the irreducible Brillouin zone (IrBZ) of reciprocal lattice in calculation of the photonic band structure. In this calculation, the photonic band structures have been simulated by the PWEM as implemented in BandSOLVE program [13] whose results are shown in Fig. 2(a-d). The photonic band gap size depends on the holes-radii (r/a) and slab-thickness (d/a) as shown in Fig. 2(a) and Fig. 2(b) respectively.

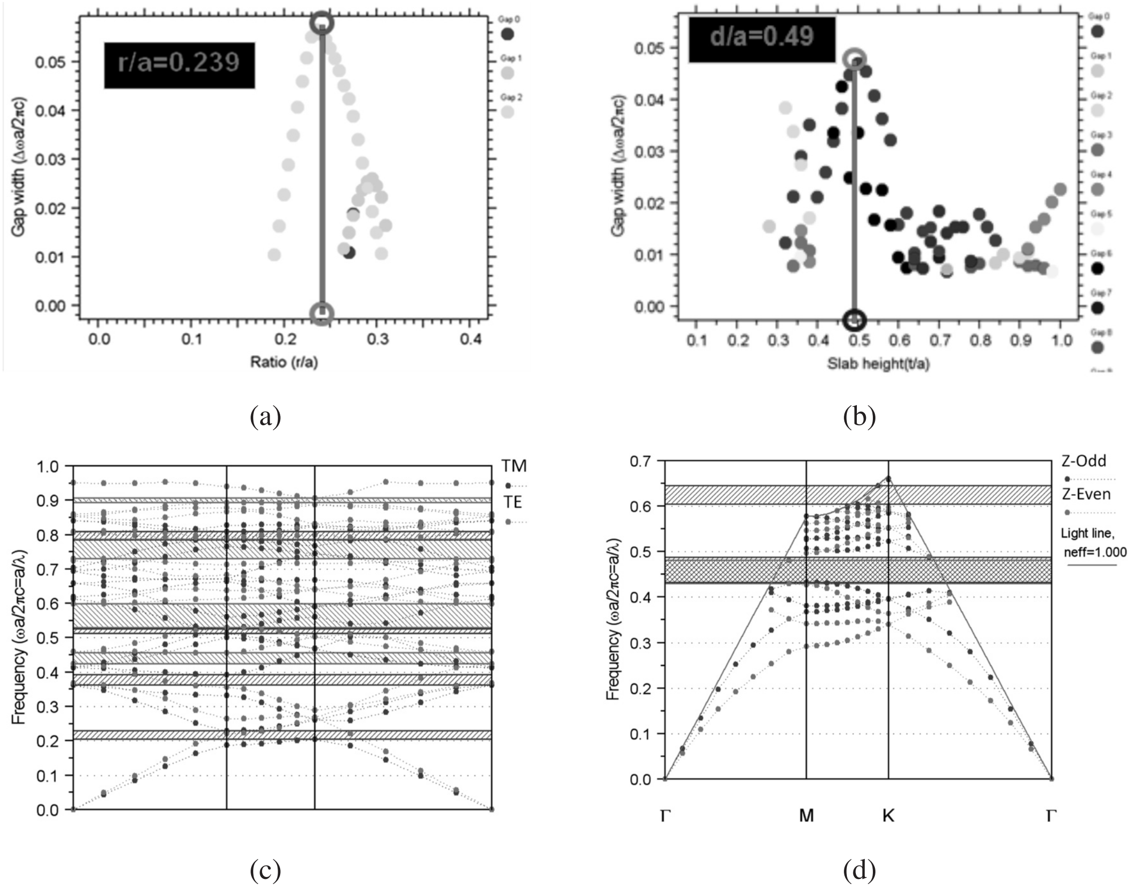
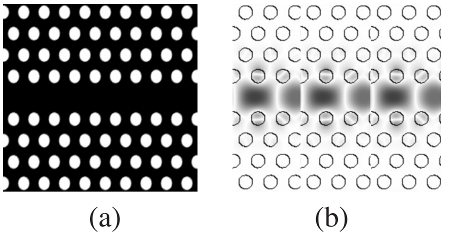


Fig. 2. Photonic band structure calculation of honeycomb lattice: (a) the holes-radii (r/a) at 0.0 to 0.4 (b) the slab thickness (d/a) at 0.1 to 1.0 (c) the complete photonic band gap (CPBG) on TE/TM mode and (d) on odd/even mode [13].

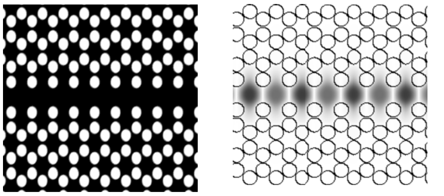
The results of the holes-radii (r/a) and slab thickness (d/a) of two-dimensional honeycomb lattice structure simulation are r/a = 0.239 and d/a = 0.49 which correspond to the largest complete photonic band gap (CPBG) - i.e. a forbidden frequency range in all directions for all polarizations-both TE/TM mode for infinite slab thickness and odd/even mode for finite slab thickness as shown in Fig. 2(c) and Fig. 2(d) respectively. The maximum mid-gap ratio is 15.38% for the first band gaps between even mode (red color) and odd mode (blue color) as shown in Fig. 2(d). For this reason, the complete photonic band gap is used to inhibit spontaneous emission of the quantum dot embedded in a planar photonic crystal waveguide at the nearest frequency range in both even mode and odd mode at the same time.

Photonic Crystal Waveguides

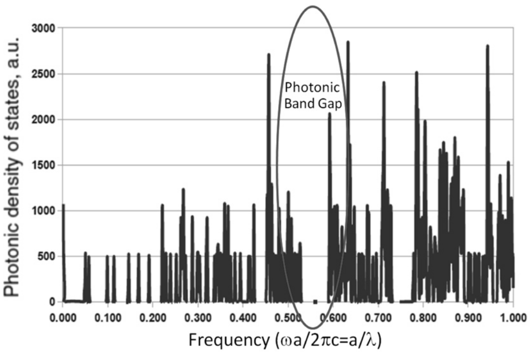
In the past few year, the controlled direction of single photon into the linear defect mode has been presented by the photonic crystal waveguide [14-17]. This has been studied and experimental tested. For example, the square lattice modifies spontaneous emission to control the single photon from Er^{3+} ion by removing one row of square dielectric rods [8]. Next, the triangular lattice modifies spontaneous emission by removing one row of air holes in the TK-direction as shown in Fig. 3(a-b) to control the single photon from self assembly quantum dots [14-17]. Thus a photonic crystal waveguide is achieved by linear defects removed or added a rows of air holes in the TK-direction as shown in Fig. 3(a,c). Then, enhancing the spontaneous emission within the photonic band gap is achieved by placing a single photon source in the center of the photonic crystal waveguide. Therefore, in this paper we propose that the single photon emission is controlled by the waveguides in the 2D photonic crystal slab arranged honeycomb lattice. This honeycomb lattice enhances the spontaneous emission by removing two rows of circular air holes in the TK-direction as shown in Fig. 3(c-d) which corresponds to guided modes of spontaneous emission at the nearest frequency range from embedded quantum dots. In order to calculate the emission properties of guided modes, the density of states must be inside second band gaps of TE mode. The display difference guided mode are shown in Fig. 3(e-f). Each guided modes (GM) propagates the single photon from an embedded quantum dot in the photonic crystal waveguide. The density of state of each guided modes relates to the difference field distributions also. This simulation of honeycomb lattice waveguide uses PWEM 2D simulation from available free software MIT Photonic Band (MPB) package [11].



(a) (b)



(c) (d)



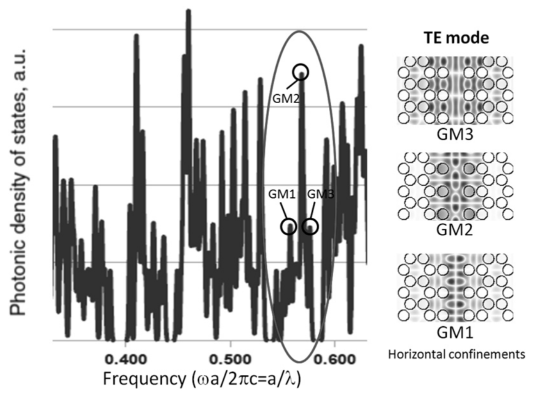


Fig. 3. Photonic crystal waveguides with removed air holes, guide mode profile and density of states. (a) Triangular lattice with one row air holes removed and (b) mode profile of guided mode in TE mode. (c) Honeycomb lattice with two rows air holes removed and (d) mode profile of guided mode in TE mode. (e) The photonic band gap (inside red ellipse region) is used to inhibit spontaneous emission and (f) the guide modes inside photonic band gap and mode profile are used to enhance spontaneous emission of the quantum dot embedded in the planar photonic crystal waveguide.

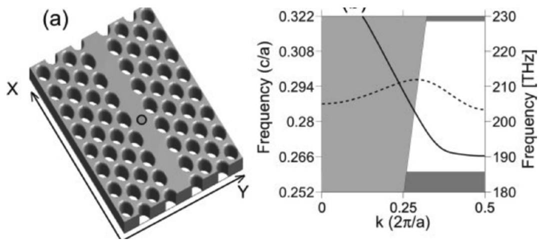
Controlling spontaneous photon emission using the photonic crystal waveguide is an important tool in applications of optical network devices such as All-optical switch, Speed or Slow light, Efficiency transmission spectrum, Optical Time-Division-Multiplexing (OTDM), Wavelength-Division Multiplexing (WDM), Super lens, Laser, LED and Single photon source base on-chip [5, 10,18].

Guided Modes

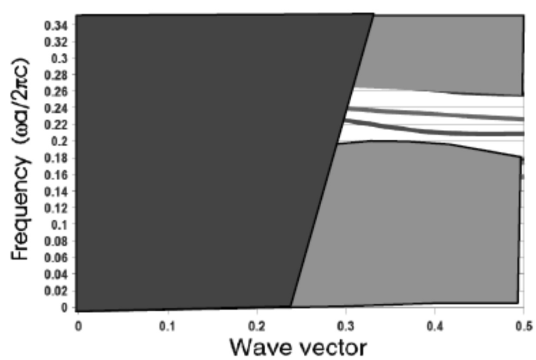
A guided mode has been represented by the density of states for electromagnetic fields. Each mode propagates out of the photonic crystal waveguide. Field distribution modes of the electromagnetic fields are classified into several modes such as monopole, dipole, quadruple and hexapole [5]. The density of states of each guided mode, which corresponds to the spontaneous emission, is controlled by some resonance frequency and decay rates of quantum dots. Therefore, we have calculated the spontaneous emission decay rate of a quantum dot positioned in the center of the photonic crystal waveguide using Ep. (6) [16-18].

$$\frac{\Gamma}{\Gamma_0} = \frac{3\pi c^3 \alpha}{V_{eff}\omega^2 \varepsilon^{3/2} v_g(\omega)} \qquad (6)$$

where Γ is the decay rate of a quantum dot in the center of the photonic crystal waveguide, Γ_0 is the decay rate in a homogeneous material, v_g is the group velocity, v_{eff} is the effective mode volume, ω is the frequency of emitter, ε is the electric permittivity, and c is the speed of light. We calculate the guided mode of the triangular lattice by removing one row in the TK-direction. The result of the guided modes is compared to the guided mode of the triangular lattice which has been studied as shown in Fig. 4(a) [14-16]. In this simulation the parameters are r/a = 0.275 and d/a = 0.5. The triangular lattice has a nearly guided mode that is 0.26 to 0.27 within the photonic band gap of the even mode as shown in Fig. 4(b). Moreover, the field distribution mode is propagating through the photonic crystal waveguide, which correspond to each the guided modes.



(a)

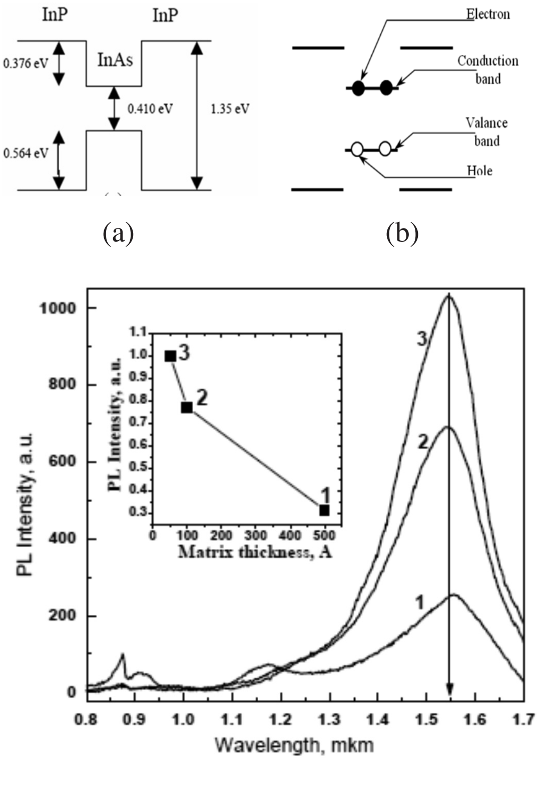


(b)

Fig. 4. The triangonal structure parameters used in our simulations:compare (a) with (b). The band structure (b) shown within TE mode of guided modes (red and blue) corresponding to 2D PhC waveguide in (a) [16-17].

Quantum Dots

Quantum dot has discrete energy levels as shown in Fig. 5(a). The quantum dots are grown from two semiconductor materials, which have different energy bands, by molecular beam epitaxial (MBE). A quantum dot is excited by the laser source which has sufficient energy. Then, electrons and holes are confined in conduction bands and valence bands as shown in Fig. 5(b) [19-20]. Finally, electrons and holes emit proton energy which corresponds to the recombination of an excitant in the quantum dots. Thus, a single photon born from the radiative recombination of electron-hole pair is confined a quantum dot with determinable energy. InAs/InGaAsN quantum dots have been grown by molecular beam epitaxy (MBE) on GaAs substrates. The InAs/InGaAsN quantum dots emitting at 1.55 μm had been demonstrated at room temperature as shown in Fig. 5(c) [21]



(c)

Fig. 5. (a-b) discrete energy levels in confined valance and conduction bands [19-20] and (c) Photoluminescence (PL) spectral of InAs/ InGaAsN quantum dots in GaAsN matrix emitting at 1.55 μm with the width 1000A (1), 200A (2), 100A (3) [21].

The photon energy caused by the recombination of the electron-hole pair that emerged from a fundamental state of a quantum dot is given by Eq. (7) [19-20].

$$E_x = E_e - E_h - J_{eh} \tag{7}$$

where E_x is the photon energy, E_e is the electron energy, E_h is the hole energy, and Jeh is the Colombien interaction between the electron and hole in the order of 10 μeV. A crucial design parameter for a single photon source using quantum dots embedded in the honeycomb lattice of the planar photonic crystal waveguide, which is the probability of single photon emitted into a waveguide mode, is given by single photon β factor. The single photon β factor is a significant design parameter for efficient photon extraction of a single photon source. The propagation mode of the single photon β factor is defined as Eq. (8) [18, 22].

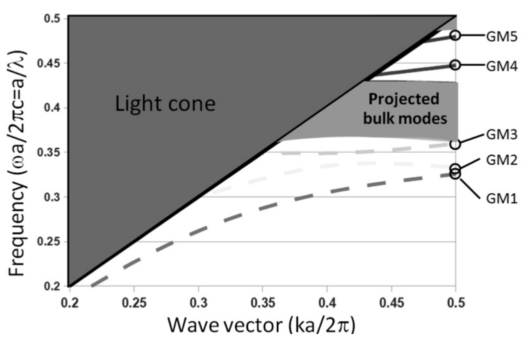
$$\beta = \frac{\Gamma_{wg}}{\Gamma_{wg}+\Gamma_{nr}+\Gamma_{rad}} \tag{8}$$

where Γ_{wg} is the decay rate of a quantum dot into the target waveguide mode, Γ_{rad} is the radiative decay rate to nonguided modes, and Γ_{nrd} is the intrinsic quantum dots nonradiative decay rate due to various dephasing processes.

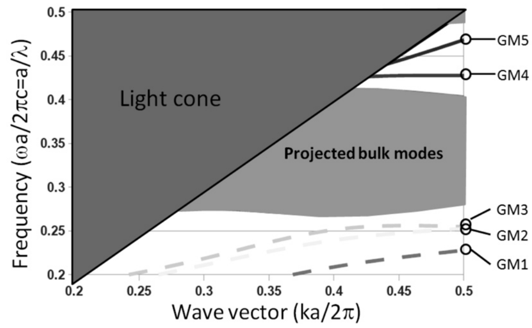
The single photon β factor is related to the manipulation of the spontaneous emission in a photonic crystal waveguide and the collected efficiency of the output single photon into a desired mode. Thus, it has been proposed in order to quantify the lasing efficiency from spontaneous emission to target waveguide mode. Furthermore, the β factor is equal to 1, corresponded to a 100% probability of emitting a single photon into waveguide mode [18, 22].

3. Results and Discussion

The photonic band structure and density of states of honeycomb lattice are simulated by PWEM as shown in Fig. 2(c) and Fig. 3(e). The second photonic band gap in the Fig. 2(c) is related to the density of state in each of frequencies in Fig 3(e). The density of states correspond to photonic band gaps that are not in the range of the frequency. The result of complete photonic band gap in Fig. 2(d) is 0.42 to 0.49 which is large enough to cover the communication wavelength range from 1.44 μm to 1.68 μm by using a lattice constant of 0.70 μm. This wavelength range does not propagate into a photonic crystal structure. Therefore, the crucial information of the wavelength range leads to the honeycomb lattice for designing the photonic crystal waveguide. In this design, we use two removed rows in the TK-direction of circular air holes from the honeycomb lattice to create a photonic crystal waveguide. This simulation uses PWEM to calculate the photonic band structure and guided modes of waveguides in a photonic crystal membrane. The results of guided mode are calculated for the photonic band structure as shown in Fig. 6(a-b).



(a)



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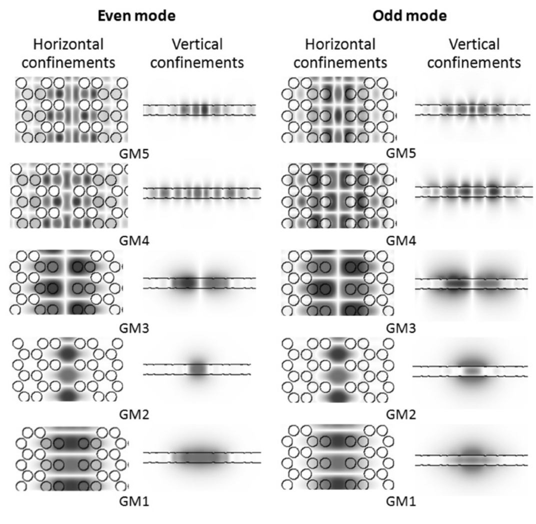

(c)

Fig. 6. Guided modes (GM) and display mode profiles of waveguide in 2D honeycomb patterned photonic crystal membrane (a) in odd mode (b) in even mode and (c) display guided mode profiles.

The results of photonic band structure for the photonic crystal waveguide are shown in Fig. 6(a-b). Each of the guided modes of odd mode and even mode has five modes which are guided at the boundary of the first Brillouin zone (K-point). The guided modes are classified into index-guided (dashed lines) and photonic-band-gap guided modes (solid lines). The index-guided modes are modes below the region of projected bulk modes (grey region). The photonic-band-gap guided modes are above the region of projected bulk modes and lie within the photonic band gap of the photonic crystal membrane. The field distributions of the five modes are shown in the (x, y)-mirror plane in the middle of the silicon membrane, so called horizontal confinement, and in the (x, z)-planes containing the high intensity, so called vertical confinement. Furthermore, these guided modes propagate through the photonic crystal waveguide with different modes. There are field distribution modes corresponding to resonance frequency in photoluminescence intensity of InAs/InGaAsN quantum dots emitting at 1.55 μm as shown in Fig. 5(c) [21].

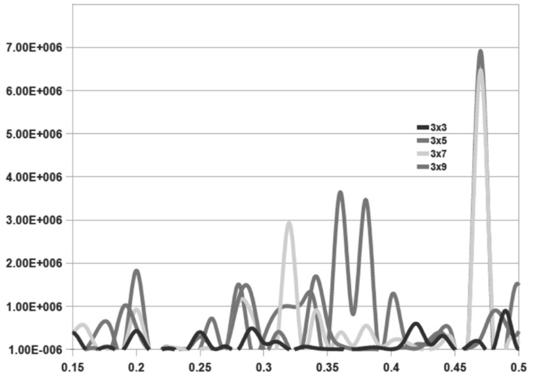

Fig. 7. Enhanced density of states of each of super cells or the number layers (3xN) inside photonic band gap of the waveguides in the honeycomb lattice.

Finally, in order to show modification and control of spontaneous photon emission from an embedded quantum dot in photonic crystal waveguide, the simple photonic crystal waveguide of honeycomb lattice is calculated by super-cell approach for the density of states and the guided modes. The number of states calculated depends on the size of the super cells or the number of layers (NxN) which is the region of the unit cell in 2D of an infinite photonic crystal waveguide. In this paper, we compared the density of states of each guided mode inside the first band gap of TE mode by the different super cells (3xN). The density of states in the first bandgap are greatly increase in each guided modes which corresponds to the complete photonic band gap of the photonic crystal membrane. Furthermore, the enlarged density of states increases of super-cells (3xN) and relates to the enhanced spontaneous emission as shown in Fig. 7. Therefore, the efficiency of single photon extraction of spontaneous emission increases in propagating mode. This simulation of the photonic crystal waveguide with the honeycomb lattice structure has been improved, that will lead to manipulation and collected efficiency for single photon source.

4. Conclusion

Inhibited and enhanced spontaneous emission of light is essential to quantum optics for designing and development of high efficiency optical devices. The triangular lattice and square lattice have been proposed for security optical communication systems before. However, we have developed an efficient single photon source by controlling spontaneous emission of the photon using the two-dimensional silicon-based photonic crystal with honeycomb lattice. The quantum dot embedded in a planar photonic crystal membrane waveguide is the light source. The structure of honeycomb lattice of circular air holes on silicon plate is simulated to obtain large complete photonic band gaps and very well guided modes for both confined horizontal and vertical directions. This significant property shows the potential application of a waveguide structure for controlling spontaneous emission between the quantum dots embedded in the two-dimensional silicon-based photonic crystal with honeycomb lattice and planar photonic crystal waveguide membrane. Significantly, this work is oriented to produce a novel single photon source which emits only one photon at a time for the quantum optical security network with a single photon state. Finally, the highly efficiency results of our calculations agree with theories and methods of quantum optics.

5. Acknowledgement

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