

Spontaneous Emission of Silicon-based on 2D Photonic Crystals Slabs with the Honeycomb Lattice and Quantum Dot

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

Keywords— Spontaneous emission, Single photon source, Photonic crystal, Honeycomb lattice, Optical communication, Optical network security

I. INTRODUCTION

Recently, quantum information technology has received considerable attention from research community and industrial sectors in various fields such as security and communications. Apart from those attenuated classical Poisson-distributed sources, demands on development of light sources whose the photon number is able to be carefully controlled with high efficiency increase significantly. In other words research attempts are to implement a single-photon source that is capable

to avoid multiple-photon generation for continuing transmission mode. Its uses encompass various applications ranging from quantum cryptography, communications and computation. In quantum system, single-photon states define bits which are technically called Qubit. Under the no-cloning theorem those quantum bits are not allowed to be duplicated without disturbing the system, i.e. noticed by receiver side [1]. Several approaches have been invented and proposed in literatures including laser excitation sources and single quantized systems, such as an atom, an ion, molecules, single quantum dots, and single nitrogen vacancy (NV) color centers in bulk diamond [2]. The self assembly quantum dots can be easily grown by Molecular Beam Epitaxial (MBE), and is then embedded in micro cavity (point defects) or waveguide (linear defect) of photonic crystal [3]. In 1887 L. Rayleigh proposed a technique that can control spontaneous emission based on Photonic Band Gap (PBG) in one Dimensional slab (1-D PhC) [4]. In 1946, E.M. Purcell predicted a spontaneous emission property of quantum dot embedded in micro cavity [5-6]. In 1987, E. Yalonovitch and S. John showed two Dimensional Photonic Crystal (2-D PhC) [4]. In 1995, J. D. Joannopoulos proposed honeycomb lattice three Dimensional Photonic Crystal (3-D PhC), which has a complete photonic band gap and a simpler fabrication than triangular lattice-based one [7]. These informations lead to conclusion that the spontaneous emission of single photon is controlled successfully by the photonic crystal. Moreover,

from theory and experiments, the photonic crystal structures 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 with quantum dot. In addition, from our study the proposed method can be applied to creation of 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 guided modes and density of states of the honeycomb lattice waveguide simulated by Plane Wave Expansion Method (PWEM) in Section III. Finally, conclusion and future work are drawn in Section IV.

II. METHOD AND MODEL

Photonic crystal waveguides both the square lattice and the triangular lattice have been developed for controlling the spontaneous emission property from the single quantized systems. Next, the two-dimensional honeycomb lattice geometry had been improved from both analysis and experiment [9]. Their properties had been controlled very suitably to modify and to control the spontaneous emission property. Based on the fact that two-dimensional honeycomb lattice features a larger photonic band gap and easier fabrication comparing to those of triangular lattice [10] we offer two-dimensional photonic crystal waveguide with honeycomb lattice whose unit cell is similar to the atomic structure of graphite. In this design, we use the silicon material slab drilled into the air hole as shown in figure 1. 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) before. In the numerical study we adopt the PWEM and super cells approach for the photonic band gap, density of state, guided modes calculations through the available free software MIT Photonic Band (MPB) package [11].

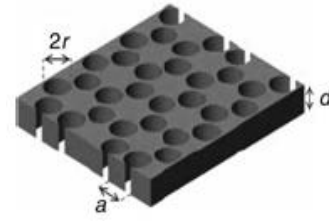


Figure 1. Photonic crystal structures of the honeycomb lattice [12].

A. Photonic Band Structure

Previously, photonic band structure both square lattice and triangular lattice in TM mode had been presented [8-10]. In designing the photonic band structure, the parameters had been optimized for control the spontaneous emission. That is $\epsilon=12$ and $r/a=0.248$ for two-dimensional simulation which correspond to the largest photonic band gap (PBG) in TM mode. For this reason, the photonic band gap is used to inhibit or enhance spontaneous emission of the quantum dot embedded in photonic crystal at the nearest frequency range. Furthermore, the photonic band gap size is depend on the holes-radii and slab thickness as the report [8, 12]. In our calculation, the photonic band structures have been performed PWEM 2D simulation as implement in MPB package. The results of the maximum mid-gap ratio as shown in figure 2 have 13% and 9% for the first (green color) and second (blue color) band gaps, respectively.

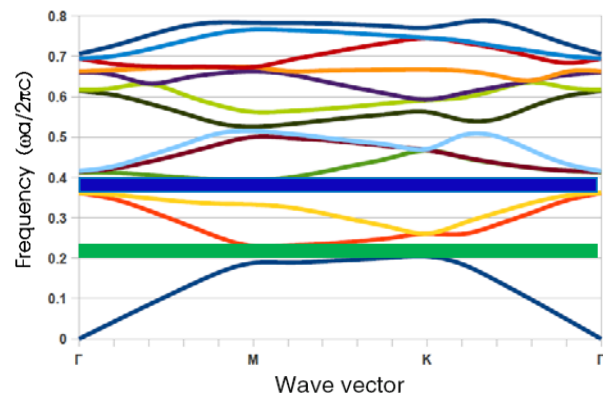


Figure 2. Photonic band structure with honeycomb photonic crystal lattice

B. Photonic Crystal Waveguides.

In the past few year, the controlled direction of single photon into the waveguide mode had been presented by the photonic crystal waveguide [13-16]. They have been studied and experimental tested. For example, the square lattice used modifies spontaneous emission for control the single photon from Er^{3+} ion by removed one row of

square dielectric rod [8]. Next to, the triangular lattice used modifies spontaneous emission for control the single photon from self assembly quantum dots [13-16]. The photonic crystal waveguide was achieved by linear defects remove or add rows of air holes in the TK-direction as shown in figure 3. Then, enhancing the spontaneous emission is achieved by placing a single photon source in the center of the photonic crystal waveguide. Therefore, in this paper to propose that the single photon emission is controlled by the photonic crystal waveguides of two-dimensional honeycomb lattice. Those parameters of structure are the ratio $r/a=0.248$ and removed two air holes in the TK-direction which correspond to guided modes of spontaneous emission from embedded quantum dots. In order to calculate the emission properties of waveguide mode that is guided modes and density of state inside photonic band gaps both first and second band gaps. The guided modes collected propagation mode of emitted single photon from embedded quantum dot in the photonic crystal waveguide. The density of state of each guided mode related to the field distributions. This simulation of honeycomb lattice waveguide used PWEM 2D simulation from available free software MIT Photonic Band (MPB) package [11]. Besides, The results of controlling spontaneous emission used the photonic crystal waveguide, which became 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, and single photon source base on-chip [5, 10,17].

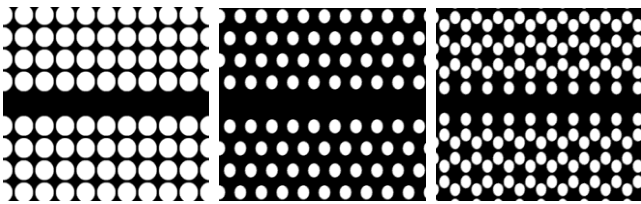


Figure 3. Photonic crystal waveguides removed one row air holes. (a) square lattice (b) triangular lattice. (c) honeycomb lattice (removed two rows).

C. Guided Modes

The guided mode has been represented by the density of state for electromagnetic fields in each mode which propagated out of the photonic crystal waveguide. Field distribution modes of the electromagnetic fields are classified into several modes such as monopole, dipole, hexapole and quadruple [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 a 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 equation (1) [14-16].

$$\Gamma = \Gamma_0 \frac{3\pi c^3 a}{V_{eff} \omega^2 \epsilon^{3/2} v_g(\omega)} \quad (1)$$

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.

c is the speed of light.

We calculated the guided mode of the triangular lattice by removing one row in the TK-direction. The result of the guided mode is compared to the guided mode of the triangular lattice which has been studied as shown in figure 4(a) [14-16]. This triangular lattice has a nearly guided mode that is 0.26-0.27 as shown in figure 4(b). Moreover, the field distribution mode is propagated through the photonic crystal waveguide, which corresponding each of guided modes.

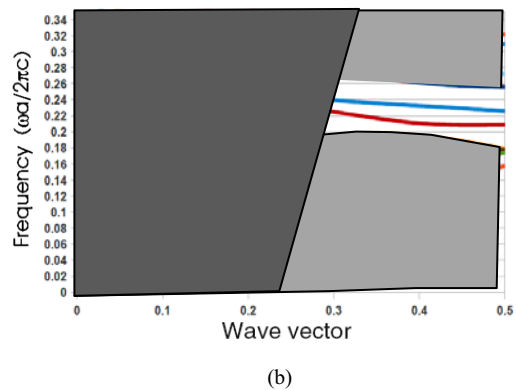
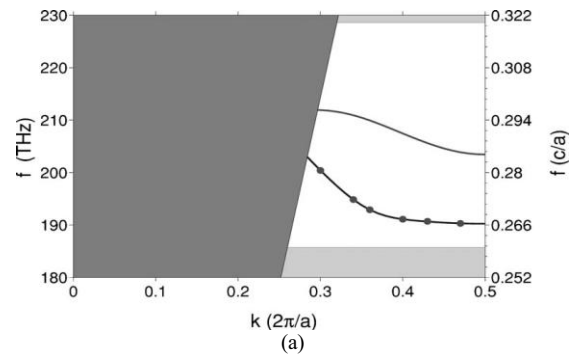


Figure 4. The structure parameters used in the our simulations compare (a) with (b) . The band structure (b) shown within TE mode of guided modes (red and blue) corresponding to 2-D PhC waveguide in (a) [15].

D. Quantum Dots

A quantum dots are discrete energy levels as shown in figure 5(a). The quantum dots are grown from two semiconductors material which is different energy bands by molecular beam epitaxial (MBE). The quantum dot is excited by the laser source which has a sufficient energy. Then, electron and holes are confined in conduction bands and valence bands as shown in figure 5(b) [18-19]. Finally, electron and holes are emitted that photon energy corresponds to the recombination of an excitant in the quantum dots. Thus, the single photon born from the radiative recombination of pair electron-hole is confined in quantum dot with determinable energy.

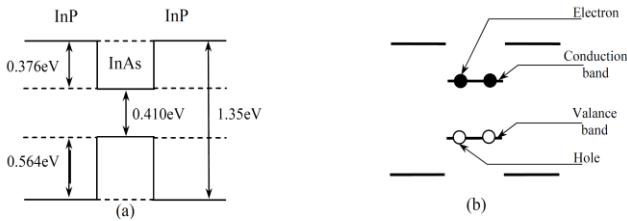


Figure 5. Discrete energy levels in confined valence and conduction bands [18-19]

The photon energy caused by the recombination of the pair electron-hole that emerged from fundamental state of quantum dot is given by equation (2) [18-19].

$$E_x = E_e - E_h - J_{eh} \quad (2)$$

E_x is the photon energy.

E_e is the electron energy.

E_h is the hole energy.

J_{eh} is the Colombien interaction between the electron and hole in order to $10\mu\text{eV}$.

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 significant of design parameter for efficient photon extraction of single photon source. The propagation mode of the single photon β factor is defined as equation (3) [15, 20].

$$\beta = \frac{\Gamma_{wg}}{\Gamma_{wg} + \Gamma_{nr} + \Gamma_{rad}} \quad (3)$$

Γ_{wg} is the decay rate of quantum dot into the target waveguide mode.

Γ_{rad} is the radiative decay rate to nonguided modes.

Γ_{nr} 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 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 single photon into waveguide mode [15, 20].

III. RESULTS AND DISCUSSION

The photonic band structure and density of states of honeycomb lattice simulated by PWEM is performed as shown in figure 2 and 6. The photonic band structures in the figure 2 are related to density of state in each of frequencies in figure 6. Frequencies haven't the density of state correspond to photonic band gaps. The results of first and second band gap are 0.206 to 0.235 and 0.365 to 0.409 respectively. The results of these frequencies are not propagated into photonic crystal structure. Therefore, the crucial information of the frequency ranges leads to investigate the honeycomb lattice for designing the photonic crystal waveguide.

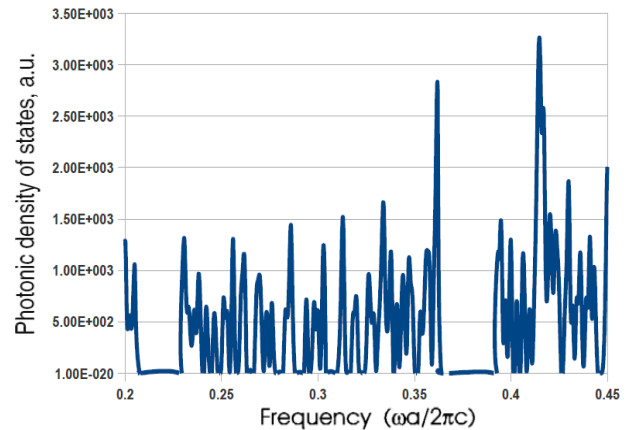


Figure 6. Density of states of the honeycomb lattice

In this design, we use two removed rows in TK-direction of air holes from the honeycomb lattice to

create photonic crystal waveguide. This simulation is used by the PWEM for the density of state of infinity photonic crystal structure and the guided modes calculations. The results of guided mode are calculated in photonic band structure as shown in figure 7. For the first bandgap, has a guided mode that is showed by the green line. Nevertheless, for the second bandgap has two guided modes, there are showed by violate and blue line. Furthermore, these guided modes are propagated through the photonic crystal waveguide with different modes of field distributions. There are the field distribution modes corresponding to resonance frequency in fundamental states of the quantum dots as shown in figure 8.

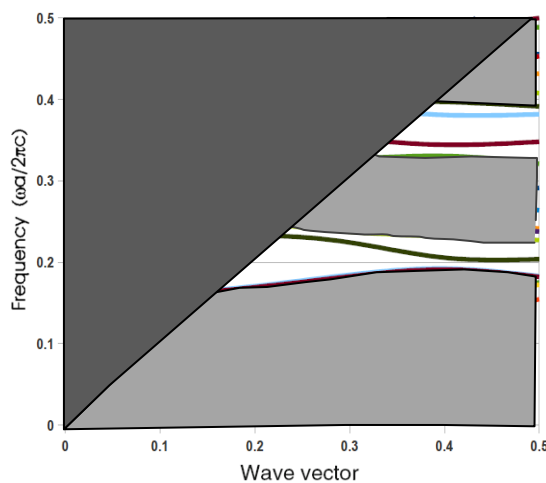


Figure 7. Guided modes of the honeycomb lattice waveguide [15].

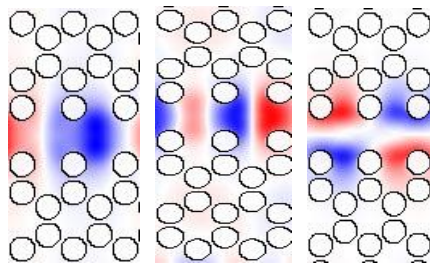


Figure 8. Propagation modes of honeycomb lattice waveguide.

Finally, in order to show modification and control of spontaneous photon emission from embedded quantum dot in photonic crystal waveguide. The simple photonic crystal waveguide of honeycomb lattice is calculated by super cells 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 layers ($N \times N$) which is region of the unit cell in photonic crystal waveguide. In this paper, we compared the density of states of each guided mode by the different super cells. The results of the density of state in the first bandgap and the second bandgap are greatly increased in each guided modes. Furthermore, the enlarged density of states varies the increase of super cells ($3 \times N$) and relate to the enhanced spontaneous emission as shown in figure 9. Therefore, the efficient single photon extraction of the enhancement spontaneous emission is increased in propagating mode. This simulation of the photonic crystal waveguide with the honeycomb lattice has been improved, that will lead to manipulation and collected efficiency for single photon source.

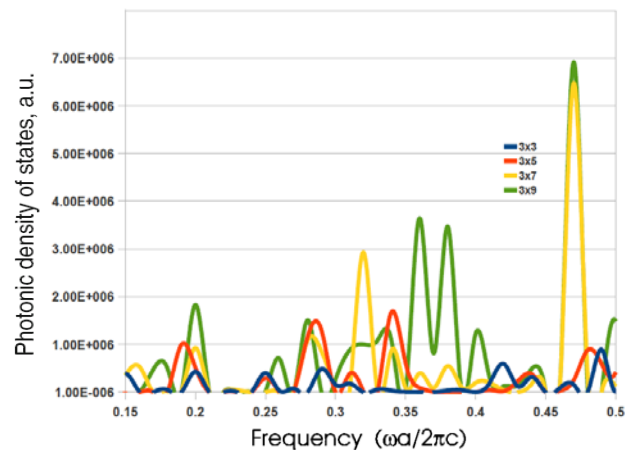


Figure 9. Density of states of each of super cells in the honeycomb lattice waveguide.

IV. CONCLUSIONS

The spontaneous emission of light is essential to quantum optics in design and development of high efficiency optical devices. The triangular lattice and square lattice have been proposed for security optical communication system before. However, we performed to develop an efficient single photon source by controlling spontaneous emission of the photon using two-dimensional silicon-based photonic crystal with honeycomb lattice. Moreover, the quantum dot embedded in planar photonic crystal membrane waveguide is the light source. The honeycomb lattice of circular air hole on silicon plate is simulated to obtain completely large

photonic band gaps. This significant property shows the potential application with waveguide structure for controlling spontaneous emission between the quantum dots embedded in the honeycomb lattice of the planar photonic crystal waveguide. Significantly, this work is oriented to produce the novel single photon sources which emit only one photon at a time for the quantum optical security network with single photon state. Finally, the highly efficiency results of our calculation are agreed with theories and methods of quantum optic.

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