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Canselori,
Universiti Sains Malaysia
Aras 6, Bangunan Canselori
11800, USM Pulau Pinang
T : (6)04-653 3108/3178/3988/5019
F : (6)04-656 6466/8470
: (6)04-653 2350
L : www.research.usm.my

No. Fail : F0256
Tarikh : 2 Disember 2011

Prof. Madya Mohd Zubir Mat Jafri
Timbalan Dekan
(Pengajian Siswazah & Penyelidikan)
Pusat Pengajian Sains Fizik
Universiti Sains Malaysia

Tuan,

LAPORAN AKHIR SKIM GERAN PENYELIDIKAN FUNDAMENTAL (FRGS)
Tajuk Projek : Simulation and Characterization of Photonic Crystals as Waveguide in Microwave Regime
No. Akaun : 203/PFIZIK/671166

Dengan hormatnya perkara di atas dirujuk.

2. Terlebih dahulu saya ucapkan ribuan terima kasih di atas satu salinan laporan akhir untuk projek penyelidikan seperti tajuk di atas.

3. Adalah dimaklumkan walaupun projek ini telah selesai, kerjasama Jabatan Bendahari dipohon untuk menguruskan penutupan akaun projek pada selewat-lewatnya **31 Disember 2011**. Tempoh ini bertujuan untuk menyelesaikan semua urusan tuntutan dan bayaran yang telah dibelanjakan di dalam tempoh projek. Walau bagaimanapun, tuan dinasihatkan supaya tidak mengeluarkan borang-borang pesanan baru di dalam tempoh ini.

4. Selanjutnya sila ambil perhatian terhadap perkara-perkara berikut sekiranya berkaitan:

(i) Semua penerbitan harus merakamkan penghargaan kepada **Skim Geran Penyelidikan Fundamental (FRGS)** dan tuan dipohon mengemukakan satu salinan ke Pejabat ini.

(ii) Bahagian Penyelidikan & Inovasi boleh/akan mengagihkan semula peralatan yang telah dibeli menggunakan peruntukan geran ini seandainya terdapat penyelidik lain yang memerlukan peralatan tersebut.

5. Akhir sekali, tahniah di atas usaha dan kejayaan pihak tuan dapat menyelesaikan projek ini dengan jayanya.

Sekian, terima kasih.

"BERKHIDMAT UNTUK NEGARA"
'Memastikan Kelestarian Hari Esok'

Yang menjalankan tugas,

(AMRA OTHMAN)
Penolong Pendaftar
Unit Pengurusan Geran & Kontrak

HAH , HAR , SM

LAPORAN AKHIR SKIM GERAN PENYELIDIKAN FUNDAMENTAL (FRGS)

Tajuk Projek : **Simulation and Characterization of Photonic Crystals as Waveguide in Microwave Regime**

No. Akaun : 203/PFIZIK/671166

s.k. Dekan Penyelidikan
Pelantar Sains Fundamental
Pejabat Pelantar Penyelidikan
Universiti Sains Malaysia

Dekan
Pusat Pengajian Sains Fizik
Universiti Sains Malaysia

Ketua Pustakawan
Perpustakaan Hamzah Sendut
Universiti Sains Malaysia

} Disampaikan satu salinan laporan akhir projek untuk simpanan Perpustakaan

Penolong Bendahari Kanan
Unit Kumpulan Wang Penyelidikan
Jabatan Bendahari
Universiti Sains Malaysia

} Mohon kerjasama pihak puan untuk menguruskan penutupan akaun projek selewat-lewatnya pada **31 Disember 2011** dan mohon kemukakan satu salinan penyata kewangan terakhir ke Pejabat ini untuk tujuan rekod

Pegawai Sains
Pelantar Sains Fundamental
Pejabat Pelantar Penyelidikan
Universiti Sains Malaysia

AO/MIS
FRGS – kampus induk/laporan akhir/tutup akaun

FINAL REPORT
FUNDAMENTAL RESEARCH GRANT SCHEME (FRGS)

Laporan Akhir Skim Geran Penyelidikan Asas (FRGS) IPT
Pindaan 1/2009

A

RESEARCH TITLE : Simulation and characterization of Photonic Crystals as Waveguide in Microwave Region
Tajuk Penyelidikan

PROJECT LEADER : Prof. Madya Mohd Zubir Mat Jafri
Ketua Projek

PROJECT MEMBERS **(including GRA)** *Ahli Projek* :
1. Prof. Madya Sohail Aziz Khan
2. Dr. Lim Hwee San
3. Mr. Wong Chow Jeng
4. Mr. Low Khee Lam

PROJECT ACHIEVEMENT *(Prestasi Projek)*

B

ACHIEVEMENT PERCENTAGE			
Project progress according to milestones achieved up to this period	**0 - 50%**	**51 - 75%**	**76 - 100%**
Percentage			95%

RESEARCH FINDINGS		
Number of articles/ manuscripts/ books	**Indexed Journal**	***Non-Indexed Journal***
	1	
Paper presentations	**International**	***National***
	2	4
Others (Please specify)		

HUMAN CAPITAL DEVELOPMENT

Human Capital	**Number**		Others (Please specify):
	On-going	**Graduated**	
PhD Student	2		
Masters Student		2	
Undergraduate Students		4	
Temporary Research Officer			
Temporary Research Assistant			
Total			

EXPENDITURE *(Perbelanjaan)*

C

Budget Approved *(Peruntukan diluluskan)*	:	**RM 36,700.00**
Amount Spent *(Jumlah Perbelanjaan)*	:	**RM 36,697.68**
Balance *(Baki)*	:	**RM 2.32**
Percentage of Amount Spent *(Peratusan Belanja)*	:	%

ADDITIONAL RESEARCH ACTIVITIES THAT CONTRIBUTE TOWARDS DEVELOPING SOFT AND HARD SKILLS
(Aktiviti Penyelidikan Sampingan yang menyumbang kepada pembangunan kemahiran insaniah)

D

International

Activity	Date (Month, Year)	Organizer
(e.g : Course/ Seminar/ Symposium/ Conference/ Workshop/ Site Visit)		

National

Activity	Date (Month, Year)	Organizer
(e.g : Course/ Seminar/ Symposium/ Conference/ Workshop/ Site Visit)		

PROBLEMS / CONSTRAINTS IF ANY *(Masalah/ Kekangan sekiranya ada)*

E Masa perlanjutan dipohon dan diluluskan. Diperlukan penyelidikan mengambil lebih masa terutama untuk penerbitan di terima serta urusan bayaran PO.

RECOMMENDATION *(Cadangan Penambahbaikan)*

F Peruntukan yang lebih besar diperlukan

RESEARCH ABSTRACT – Not More Than 200 Words *(Abstrak Penyelidikan – Tidak Melebihi 200 patah perkataan)*

G

This project is to study the fundamental characteristic of photonic crystals in microwave region. The most unique characteristic of this structure is the band gap which can be observed from the band structure graph of photonic crystals. So, we denoted the plane wave expansion method to study the band structure graph of the photonic crystals. Several materials are used to create the photonic crystals. Plane wave expansion method is modified to investigate the metals material. This is because more characteristic can be observed in metal materials compared to the conventional. We found that there is wave activities below the plasma frequency which is not occured for a conventional metals structure. So, we studied the effective plasma frequency of the photonic crystals.

Date : 14 Sept. 2010
Tarikh

Project Leader's Signature:
Tandatangan Ketua Projek

Prof. Madya Mohd. Zubir Mat Jaf...
Timbalan Dekan
(Pengajian Siswazah dan Penyelidikan)
Pusat Pengajian Sains Fizik
Universiti Sains Malaysia
11800 Pulau Pinang

COMMENTS, IF ANY/ ENDORSEMENT BY RESEARCH MANAGEMENT CENTER (RMC)
(Komen, sekiranya ada/ Pengesahan oleh Pusat Pengurusan Penyelidikan)

H ....

....

....

Name:
Nama:

Signature:
Tandatangan:

Date:
Tarikh:

SIMULATION AND CHARACTERIZATION OF PHOTONIC CRYSTALS AS WAVEGUIDE IN MICROWAVE REGION

Assoc. Prof. Dr. Mohd Zubir Mat Jafri
Assoc. Prof. Dr. Sohail Aziz Khan
Dr. Lim Hwee San
En. Wong Chow Jeng
En. Low Khee Lam
Universiti Sains Malaysia/School of Physics
mjafri@usm.my
Pure Science

ABSTRACT (120 words)

This project is to study the fundamental characteristic of photonic crystals in microwave region. The most unique the character of this structure is the band gap which can observe from the band structure graph of photonic crystals. So, we denoted the plane wave expansion method to study the band structure graph of the photonic crystals. Several materials are used to create the photonic crystals. Plane wave expansion method is modified to investigate the metals material. Then, from the band structure graph, we created the photonic crystals waveguide.

1. INTRODUCTION

Photonic crystals or electromagnetic band gap is a repeating construction which exhibits useful band rejection for electromagnetic wave. This periodic structure has been widely used in optical application. One dimension photonic crystal is normally worked as filter for electromagnetic wave. Two dimension and three dimension photonic crystal are normally used for wave guide application.

Photonic crystals provide a promising tool to control the flow of light in integrated optical devices [1]. Therefore, there is great deal of interest in developing photonic crystals based waveguide where one can confine and effeciently guide the light around sharrp corners [2-5].

The basic motivation in photonic crystal based waveguides arose when the following properties of the photonic band gap material (PBG), which are essential for many applications, were considered. First, photonic crystals have the property of reflecting the EM waves within the band gap frequencies in all directions. Second, defect structures in which the EM wave is trapped, can be created by breaking the periodicity of the crystal.[4] These two properties have proved that the photonic crystals may serve as waveguide. Once the EM wave is coupled inside the guide, the trapped wave, which has no where else to go, is guided through the opening inside the crystal. This guiding mechanism is superior to traditional waveguides which rely on total internal reflection of the EM waves

2. RESEARCH METHODOLOGY

From the Bloch Theorem (1D: Floquet's), we know that wave can propagate in the PC without scattering. So, for the most of the wavelength λ, beams propagate through the PC without scattering but for λ~2a which a is the distance between each lattice, wave can not propagate. So this is the forbidden gap. From the Maxwell Equation,

$$\nabla \times E = -\frac{1}{c}\frac{\partial}{\partial t} H = i\frac{\omega}{c} H \qquad 1.1$$

$$\nabla \times H = \varepsilon \frac{1}{c}\frac{\partial}{\partial t} E + \frac{4\pi J}{c} = i\frac{\omega}{c}\varepsilon E \qquad 1.2$$

dielectric function $\varepsilon(\mathbf{x}) = n^2(\mathbf{x})$

$$\underbrace{\nabla \times \frac{1}{\varepsilon} \nabla \times}_{\text{Operator}} \vec{H} = \underbrace{\left(\frac{\omega}{c}\right)^2}_{\text{Eigen value}} \underbrace{\vec{H}}_{\text{Eigen state}} \qquad 1.3$$

$$\left(\frac{1}{\varepsilon_r}\nabla\times\nabla\times\right)\vec{E} = \left(-\frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)\vec{E} \qquad 1.4$$

Then, we seek a steady state harmonic solutions of the form

$$\vec{H}(t,\vec{r}) = \vec{H}(\vec{r})e^{j\omega t} \qquad 1.5$$

$$\vec{E}(t,\vec{r}) = \vec{E}(\vec{r})e^{j\omega t} \qquad 1.6$$

Where ω is the angular eigenfrequency, and $\vec{H}(\vec{r})$ and $\vec{E}(\vec{r})$ are the eigenfunctions of the wave equations. The permittivity of medium $\varepsilon(\vec{r}) = \varepsilon_0\varepsilon_r(\vec{r})$ at any given frequency may depend on the spatial coordinate. The refractive index is defined by Maxwell's formula $n = \sqrt{\varepsilon_r\mu_r} = \sqrt{\varepsilon_r}$. We need to define the complex permittivity $\bar{\varepsilon}_r$ with real part ε_r and imaginary part $-\varepsilon_{ri}$, the complex refractive index $\bar{n}$ with real part n and imaginary part $-n_i$ for the properties of real media. For the passive microwave materials, the loss factor $\tan\delta = \varepsilon_r / \varepsilon_{ri}$ is usually specified.

$$\bar{n} = n - \mathrm{j}n_i = \sqrt{\bar{\varepsilon}_r} \qquad 1.7$$

$$\bar{\varepsilon}_r = \varepsilon_r - j\varepsilon_{ri} = \bar{n}^2 \qquad 1.8$$

In order to analyze the Maxwell Equation's and properties of the media, we will use the finite difference time domain method (FDTD). To connect these field distributions to the usual circuit quantities of voltage and current, the following fundamental expressions will be used:

$$V(t,x_i) = \int_{C_v} \bar{E}(t,x_i) \bullet d\bar{l} \qquad 1.9$$

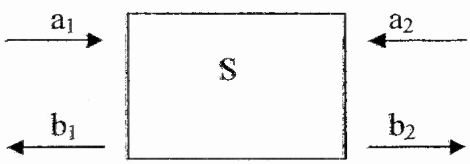
$$I(t,x_i) = \oint_{C_I} \bar{H}(t,x_i) \bullet d\bar{l} \qquad 1.10$$

where C_v is a contour extending from a defined voltage reference point to the circuit xi. Similarly, contour C_I to wrap completely around the strip conductor at its surface in the transverse plane provides the load current.

For studying the loss of the photonic crystals, we will look into the scattering matrix. For a single mode in wave guide, the transmissions and reflection methods are shown in matrices as below:

$$\begin{pmatrix} b_1 \\ b_2 \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \end{pmatrix} \qquad 1.11$$

where a, b are the wave amplitudes.



To investigate the return loss, S_{11} will be considered. From (2.1),

$$S_{11} = \left.\frac{b_1}{a_1}\right|_{a_2=0} \qquad 1.12$$

To investigate the insertion loss, S_{21} will be considered. From (2.1),

$$S_{21} = \left.\frac{b_2}{a_1}\right|_{a_2=0} \qquad 1.13$$

Graph will be plotted again frequency.

Finally, after the computation analysis of the data, a summary on optimizing the design of the photonic crystals will be made. For this purpose, we use commercial simulation software to design and optimizing the photonic crystals. The software is High Frequency Structure Simulator. By using this software, we can design the photonic crystals we need and run a simulation on it. It will give us the return loss and insertion loss results against frequency. So, we will also validate our study.

3. LITERATURE REVIEW

Photonic crystals has been studied rigorously in this decade. First, the study was lead by Yablonovitch and Sajeev [6, 7] in 1987 which they found that the periodic dielectric can control the flow of light and this caused the born of photonic crystals in Physics. This is the beginning of the photonic crystals research in the scientific area. It has become one of the most leading researches in the world where scientists try to understand the basic characteristic of the photonic crystals. They used the fundamental physics of solid state to study it. Bloch theorem, reciprocal lattice and Brillouin zones were adapted from the original understanding. Due to the close relationship between periodic energy, band structure graph is used to describe the propagation of the wave for photonic crystals. It can show the stop band and propagation band of the photonic crystals. As we can see in Figure 1 an example of band structure, the shaded grey area is the stop band of the designed photonic crystals. Wave propagation is not allowed in this area. This is because the wave is destructed and there is no energy band. The entire wave is rejected in this area and this made the very special characteristics of PC where only PC can make it. The extensive development of solid state has opened the gate of the semiconductor technology. It built a strong base of manipulating the current development on the semiconductor but it was still not enough. Although scientists had the strong knowledge about propagation electron in solid, they are looking forward to manipulate the light or wave in solid. This breakthrough finding will bring the new era of information technology.

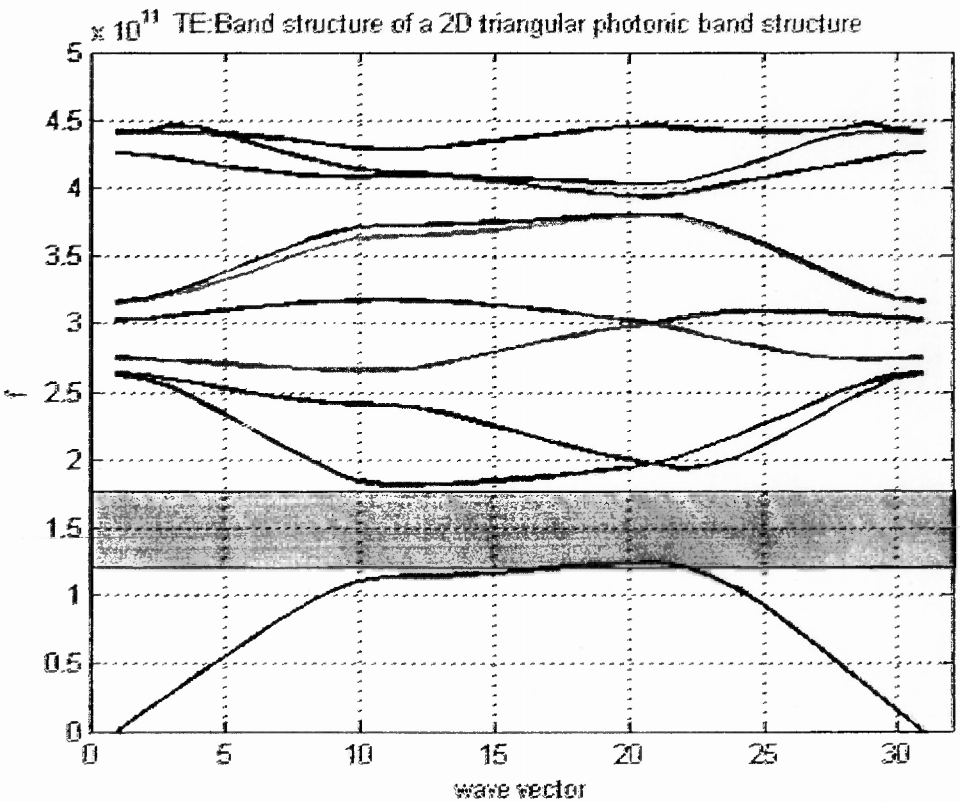


Figure 1 Dispersion graph of the photonic crystals. 2-dimension triangular lattice with Galium Arsenide as background material and embedded with vacuum rods.

Band structure graph is used to determine the working frequency, structure dimension and losses of the photonic crystals. Then, this can lead to the application in antenna, filter and waveguide. We can create PC with its characters of reflection, localization, refraction, and transmission. Each of these characters can be used to create unique devices that currently being used with lower losses. Example, with the localization characteristic of PC, we can design a waveguide [2, 4, 5, 8-10]; with band gap characteristic, we can design a reflecting mirror [6, 11]; with refraction characteristic, we can design a super prism phenomena [12] and negative refraction[13]. Due to these unique characteristics of photonic crystals, scientists have thought of using photonic crystals arrangement for photonic circuits. Photonic crystal is used to control the flow of photon in the photonic circuits as shown in Figure 2. This is the illustration by G. Johnson from MIT which he believed that this is the future of photonic circuits. Each of its components was made by photonic crystals. Besides that, photonic crystals also can be used to confine the flow of microwave. So, photonic crystals lie in the general objective of micronanophotonics devices.

The basic characteristics of photonic crystals have driven the photonic crystals to replace the conventional design of electronic devices. There are a few examples of replacement which are antenna [14-17], fiber optic[18-20], laser[21], microstrip [22-26], filter [27], photonic circuits[28], superconductor[29], solar cell[30], perfect lens[31], horns[32], waveguide [10, 33, 34] and biomedical and chemical sensor[35, 36]. Scientist also starts to use metallic photonic crystal to study the effect of surface plasmon polaritons.[37-41] Recently, scientists also found out that we can tailor the plasma frequency of metallic as desired.[41-43] The result is promising. PC made from plasma material also has been studied by several scientists.[42-44] So, band structure graph is very important to be used to design and characterize all the devices mentioned above.

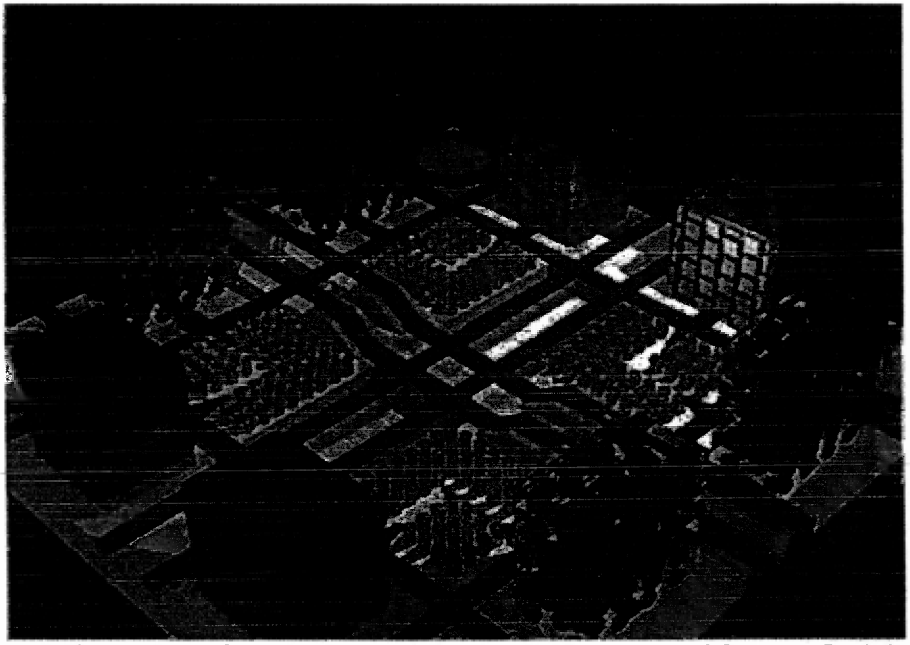


Figure 2 Illustration of photonic crystals circuit (Courtesy of Steven G. Johnson)

4. FINDINGS

We have successfully plotted the band structure graph for several dielectric materials in microwave region. Plane wave expansion method has been modified for the investigation of metals materials. So, an improved equation for plane wave expansion method has been derived for the calculation of band structure graph. Then, from the band structure graph the group velocity of the wave has been discussed for the application of waveguide. Group velocity anomaly was detected in band edges of several materials. This characteristic can be used for the enhancement of photonic devices. Surface plasmons were also detected. This interesting feature can be used for the terahertz application.

5. CONCLUSION

Finally, we have plotted several band structure graphs of different materials which included frequency dependant material. Group velocity anomaly and surface plasmons were detected in the band structure graph. So, detailed discussion has to be done in future investigation.

ACHIEVEMENT

i) Name of articles/ manuscripts/ books published

LOW, K. L., JAFRI, M. Z. M. & KHAN, S. A.,2009. Band Gap Study Using Plane Wave Expansion Method for Metallic Slab with Air Rods in E Polarizing Mode. *Chinese Journal of Physics,* 47, pp.853.

ii) Title of Paper presentations (international/ local)

LOW, K. L., JAFRI, M. Z. M. & KHAN, S. A.,2008. Band Gap Calculation for Two Layered PEC Electromagnetic Band Gap Structure in Application of Microstrip. *IEEE INTERNATIONAL RF AND MICROWAVE CONFERENCE.* Kuala Lumpur, IEEE.

LOW, K. L., JAFRI, M. Z. M. & KHAN, S. A.,2009. Band Gap Calculation on 2D Square Lattice Metallic Slab Photonic Crystals with Air Rods. *3rd International Meeting on Frontiers of Physics 2009.* Kuala Lumpur, Malaysia.

LOW, K. L., JAFRI, M. Z. M. & KHAN, S. A.,2009. Group Velocity of 2D Square Lattice Metallic Medium Photonic Crystals with Air Rods in E polarization Mode. *International Advanced of Technology Congress (ATCi).* Kuala Lumpur, Malaysia.

LOW, K. L., JAFRI, M. Z. M., KHAN, S. A. & WONG, C. J.,2007. A simulation study on two straight photonic crystals in microwave range. *International EMF Conference 2007.* Kuala Lumpur.

LOW, K. L., JAFRI, M. Z. M., KHAN, S. A. & WONG, C. J.,2007. A Study of Photonic Crystals as Waveguide in Microwave Region. *International EMF Conference 2007.* Kuala Lumpur.

LOW, K. L., JAFRI, M. Z. M., KHAN, S. A. & YUSOF, A. J. B.,2008. Characteristic of 2D Triangular Lattice of Photonic Crystals for Microwave and Photonic Devices. *SPIE Europe Security and Defense.* University of Wales Institute, Cardiff, UK, SPIE.

LOW, K. L., JAFRI, M. Z. M., KHAN, S. A., YUSOF, A. J. B., WONG, C. J. & ABDULLAH, F.,2007. A Computation Study of Digital Signal on a Microstrip Lines. *Asian Physics Symposium 2007.* Bandung, Indonesia.

iii) Human Capital Development

iv) Awards/ Others

v) Others

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APPENDIXES

Band Gap Calculation Using the Plane Wave Expansion Method for Metallic Substrate Photonic Crystals (PC) with Air Rods in E Polarizing Mode

K. L. Low, M. Z. Mat Jafri, and Sohail A. Khan

Universiti Sains Malaysia, Penang, Malaysia
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By using the plane wave expansion method, we have calculated the band gap for a metallic slab with air rods in the transverse magnetic (TM) mode. The metallic structure of this system is an identical, symmetric structure and an infinite array of air rods. The arrangement of the air rods we used are a square lattice and a triangular lattice. The dielectric function of the metallic substrate is of the free electron form $\varepsilon(\omega)$=1-(ω_p^2/ω^2), where ω_p is the plasma frequency of the conducting electron. We present the band structure of the square lattice and triangular lattice.

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I. INTRODUCTION

Photonic crystals are periodic dielectric structures. They were studied by Yablonovitch [1]. He considered the photonic crystals by solving the Maxwell equation and found the analogy between the wave propagation in periodic crystals and the electron propagation in real crystals. He pointed out the importance of the band gap which occurs in the band energy of the photonic crystals. The existence of the band gap can help to mold the flow of the light. It can localize and guide the flow of photons in the structure. The effort of finding a method to solve the band energy continued after that. There have been many proposed methods [2–8]. They include using the plane wave expansion method (PWE), finite differences time domain (FDTD), and super cell and finite differences frequency domain (FDFD). Each method has it own limitations for finding the band structure. PWE was used for finding the band structure which is normally symmetric, and FDTD or FDFD was used for any complex structure. But PWE uses less computational time. As for the band gap calculation, the material used includes non-frequency dependent materials to frequency dependent materials. Non-frequency dependent material was investigated rigorously but not the frequency dependent materials. Frequency dependent material here means a metallic material like copper, silver, gold, aluminum, etc. In 1994 [4], the first calculation was made to calculate the photonic crystals containing a metallic structure in air using the PWE method. The dielectric function was formed as

$$\varepsilon(\omega) = 1 - (\omega_p^2/\omega^2), \tag{1}$$

where ω_p is the plasma frequency of the conduction electrons.

The motivation of this paper is due to the wide applications of microstrips, antennas, filters, etc. in which the structure normally contains a metallic substrate. Furthermore, metallic structure was limited for higher frequency waves to more than 10 GHz [9]. This phenomenon was explained due to the metal's electron drifting when the frequency is that high. Although there are various methods to find the band structure of metallic cylinders, a metallic slab still lacks consideration. So, in this paper we calculated the band gap structure of a metallic substrate with an air cylinder. We continue the PWE method and modify the dielectric periodic constant of the photonic crystals to meet the need here. The mode we focused on here is the E polarization mode or transverse magnetic mode (TM). This is the mode which will be guided through.

II. MATHEMATICAL FORMULATION

II-1. Basic

The 2D structure is shown in Figure 1. We assumed the periodic structure is along the z axis. So, we turned the Bravais lattice into a vector form as

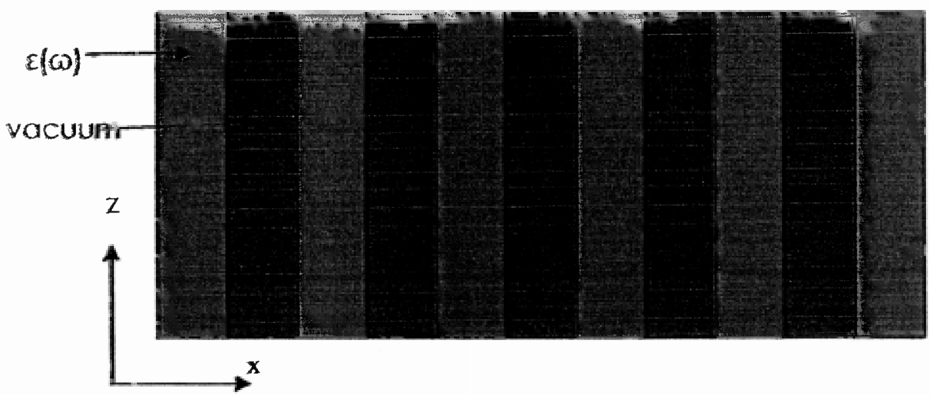

FIG. 1: Cross section view of the 2D periodic structure.

$$x = l_1 a_1 + l_2 a_2. \tag{2}$$

The dielectric constant of the structure along x should fulfill the following characteristic:

$$\varepsilon\left[x + x(l)\right] = \varepsilon\left(x\right). \tag{3}$$

Therefore, we expand it into a Fourier form,

$$\varepsilon'(x) = \sum_{,} \varepsilon'(G) e^{-iG\cdot x}, \tag{4}$$

where G is the reciprocal lattice and the Fourier coefficient is

$$\varepsilon'(G) = \frac{1}{a_c} \int_G d^2x \varepsilon'(x) e^{-iG\cdot x}. \tag{5}$$

II-2. Modification

We modify and construct the dielectric periodic function to meet the requirement of the metallic structure we proposed, as is shown in Figure 1. We formulate it in

$$\varepsilon''(x) = \varepsilon(\omega) + [1 - \varepsilon(\omega)] \sum_l S[x - x(l)], \tag{6}$$

where $S(x) = 1$ if x is inside the cross section of the cylinder centered at the origin of coordinates and $S(x) = 0$ if x is outside this cross section. We compare Equation (6) with Kuzmiak's calculation [4], which is stated as

$$\varepsilon(x) = 1 + [\varepsilon(\omega) - 1] \sum_l S[x - x(l)]. \tag{7}$$

Equation (6) is modified from the work of Kuzmiak. We switch the position of the dielectric constant between metallic rods and air. The equation fulfills the periodic behavior of the structure. After that we make the comparison, we found that both of the equations can be combined and transform into the equation

$$\varepsilon''(x) = -\varepsilon(x) + 1 + \varepsilon(\omega). \tag{8}$$

So, in this case we can expand Equation (8) in a Fourier transform

$$\varepsilon''(G) = -\frac{1}{a_c} \int_G d^2x \varepsilon(x) e^{-iG\cdot x} + \frac{1}{a_c} \int_G d^2x \, [1 + \varepsilon(\omega)] \, e^{-iG\cdot x}, \tag{9}$$

we get as the final equation

$$\varepsilon''(G) = \left[1 - \frac{\omega_p^2}{\omega^2}\right] \delta_{G,0} + \left[\frac{\omega_p^2}{\omega^2}\right] \frac{1}{a_c} \int_G d^2x s(x) e^{-iG\cdot x}. \tag{10}$$

We assume that when $G = 0$ the dielectric constant is

$$\varepsilon''(G) = \left[1 - \frac{\omega_p^2}{\omega^2}\right] \delta_{0,0} + \left[\frac{\omega_p^2}{\omega^2}\right] \frac{1}{a_c} \int_G s(x) d^2x, \tag{11}$$

where $\delta_{0,0} = 1$, $\frac{1}{a_c} \int_G s(x) d^2x = f$, so

$$\varepsilon''(G) = 1 + \left[\frac{\omega_p^2}{\omega^2}\right] (f - 1). \tag{12}$$

We also assume that when $G \neq 0$ the dielectric constant is

$$\varepsilon''(G) = \left[1 - \frac{\omega_p^2}{\omega^2}\right] \delta_{G,0} + \left[\frac{\omega_p^2}{\omega^2}\right] \frac{1}{a_c} \int\limits_G d^2x s(x) e^{-iG\cdot x}, \tag{13}$$

where $\delta_{G,0} = 0$, $\frac{1}{a_c} \int\limits_G s(x) e^{-iG\cdot x} d^2x = 2f \frac{J_1(|G|R)}{|G|R}$, so

$$\varepsilon''(G) = 2f \left[\frac{\omega_p^2}{\omega^2}\right] \frac{J_1(|G|R)}{|G|R}. \tag{14}$$

II-3. Application

After the calculation of the dielectric, which is most important for finding the band gap, we will apply Maxwell's equations. In this application, we would like to consider only the E polarization mode or transverse magnetic mode.

In the TM mode (E polarization) $E_3(x|\omega)$ is obtained as

$$E_3(x|\omega) = \sum_G B(k|G) e^{i(k+G)\cdot x}, \tag{15}$$

where k is the wave vector of the wave. Then, we obtained an equation (16) satisfied by the coefficients $B(k|G)$:

$$\begin{aligned} (k+G)^2 B(k|G) &= \frac{\omega^2}{c^2} \sum_{G'} \varepsilon(G-G') B(k|G) \\ &= \frac{\omega^2}{c^2} \varepsilon(0) B(k|G) + \frac{\omega^2}{c^2} \sum_{G'} \varepsilon(G-G') B(k|G). \end{aligned} \tag{16}$$

The use of the results of Equations (12) and (14) into Equation (16) which transforms the latter into

$$\begin{aligned} &(k+G)^2 B(k|G) - f\frac{\omega_p^2}{c^2} B(k|G) + \frac{\omega_p^2}{c^2} B(k|G) - \frac{\omega_p^2}{c^2} \sum_{G'} 2f \frac{J_1(|G-G'|R)}{|G-G'|R} B(k|G) \\ &= \frac{\omega^2}{c^2} B(k|G) \sum_{G'} \left[(k+G)^2 \delta_{G,G'} + \frac{\omega_p^2}{c^2} \delta_{G,G'} - \frac{\omega_p^2}{c^2} 2f \frac{J_1(|G-G'|R)}{|G-G'|R}\right] \times B(k|G) \\ &= \frac{\omega^2}{c^2} B(k|G). \end{aligned} \tag{17}$$

III. RESULTS AND DISCUSSION

Equation (17) is a Hermitian Matrix. It has eigenvalues that need to be found. This is a standard eigenvalue problem that can numerically be solved. We used copper as the metal slab and a vacuum for the cylinder rods. The plasma frequency of copper is 1914 THz [10]. We applied this equation into 2 different lattice arrangements. First, we will use the square lattice arrangement and then the triangular lattice arrangement.

1. Square lattice

We first consider a simple square lattice arrangement. The lattice parameter is a for which the primitive translation vectors are

$$\mathbf{a}_1 = a(1,0), \quad \mathbf{a}_2 = a(0,1), \tag{18}$$

while the vectors of the reciprocal lattice are

$$\mathbf{b}_1 = \frac{2\pi}{a}(1,0), \quad \mathbf{b}_2 = \frac{2\pi}{a}(0,1). \tag{19}$$

The filling fractions of the square lattice air rods in the metallic slab are $f = \pi R^2/a^2$.

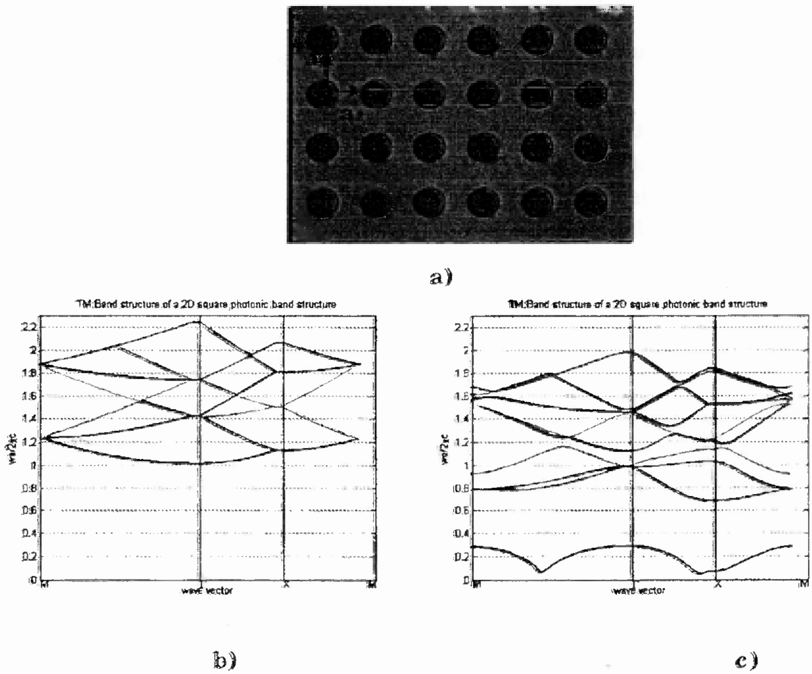

FIG. 2: (a) Square lattice arrangement. (b) Band structure of 2D square lattice with filling factor= 0.0001, $a = 1$ mm, and $R = 0.0056$ mm, (c) filling factor= 0.3, $a = 1$ mm, and $R = 0.3090$ mm.

The arrangement of the square lattice is shown in Figure 2(a). The photonic band gap is presented in Figure 2(b) and 2(c) with different filling fractions. We used a total of 121

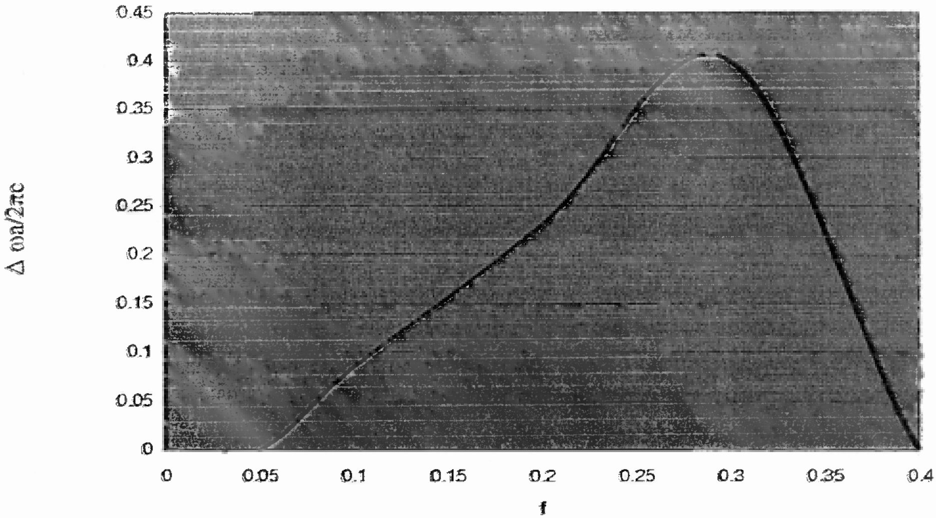

FIG. 3: The width of the square lattice band gap plot against the filling fraction.

waves to propagate through the structure to obtain the graphs. When the filling fraction f=0.0001, no band gap occurred. But when it reaches f=0.3, the width of the band gap is about 0.4, which is shown in Figure 2(b) and 2(c) respectively. In Figure 2(c), the gap occurs between the first band and the second band. There will be no band gap beyond that. This is a very common phenomenon in photonic crystals [2–4]. We illustrate the relation between the size of the band gap and the filling fraction in Figure 3. We obtained an optimum size during f=0.3. In this lattice arrangement, the band gap appears when $f \geq 0.05$ and the band gap disappears when $f \leq 0.4$.

1. Triangular lattice:

The primitive vectors are

$$\mathbf{a}_1 = a(1,0), \quad \mathbf{a}_2 = a(\frac{1}{2}, \frac{1}{2}\sqrt{3}), \tag{20}$$

then the reciprocal translation vectors are

$$\mathbf{b}_1 = \frac{2\pi}{a}(1, -\frac{1}{3}\sqrt{3}), \quad \mathbf{b}_2 = \frac{2\pi}{a}(0, \frac{2}{3}\sqrt{3}). \tag{21}$$

The filling factors of the triangular lattice air rods in the metallic slab are $f = (2\pi/\sqrt{3})R^2/a^2$

Figure 4a is the arrangement of the triangular lattice. We used a total of 121 waves to obtain the band structure illustrated in Figure 4b and 4c. In Figure 4b, we used the

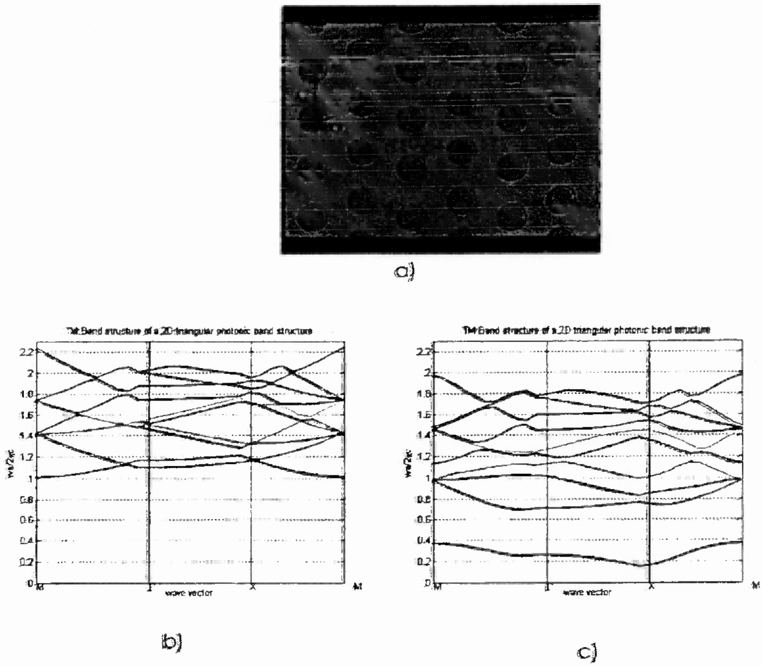

FIG. 4: a) Triangular lattice arrangement. b) Band structure of 2D triangle lattice with filling factor= 0.0001, $a = 1$ mm, $R = 0.0053$ mm; c) filling factor= 0.3, $a = 1$ mm and $R = 0.2876$ mm.

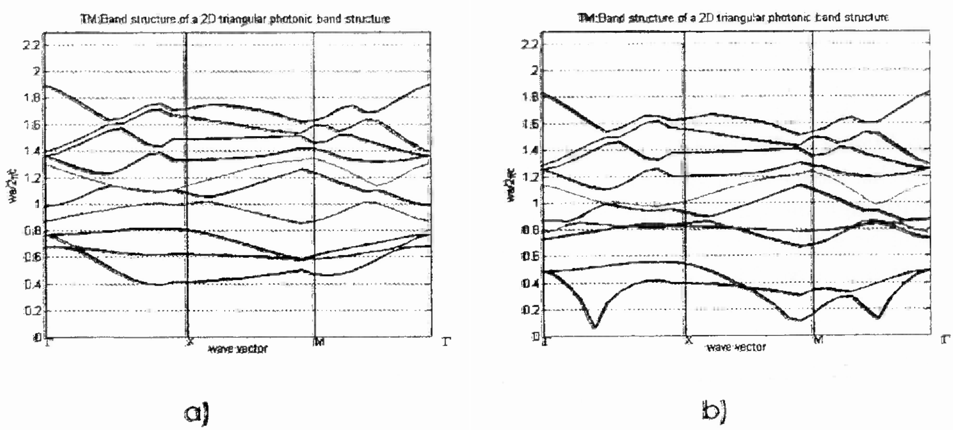

FIG. 5: a) Band structure of a 2D triangle lattice with filling factor= 0.4, $a = 1$ mm, $R = 0.3321$ mm; b) filling factor= 0.5, $a = 1$ mm, and $R = 0.3713$ mm.

filling fraction f=0.0001. No band gap appears in this filling fraction. In Figure 4c, we use f=0.3 and a band gap appears in this structure. As usual, the gap only appears in between the first band and second band. The band structure shows that the band gap appears in between the third band and fourth band for Figure 5a, while there is a second band and third band for Figure 5b. Figure 5a shows the band structure of the photonic crystals with f=0.4 and Figure 5b for f=0.5. This phenomenon is very rare.

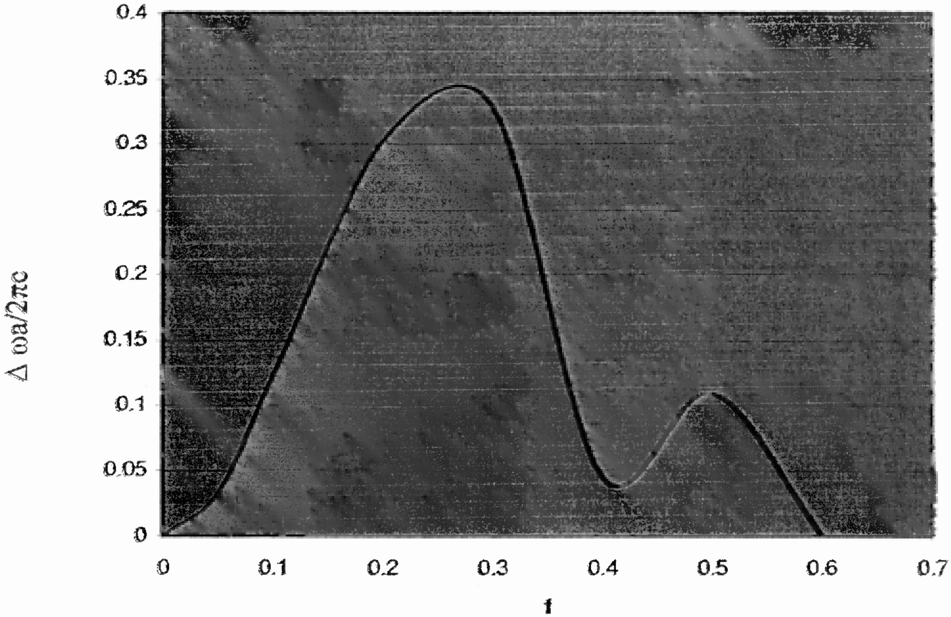

FIG. 6: The width of the square lattice band gap plot against the filling fraction.

We plot the relation between the gap size and the filling fraction. This is illustrated in Figure 6. We find that there are 2 peaks, although another one is smaller when f=0.5. In this lattice arrangement, the gap appears when $f > 0$ and only disappears when $f \leq 0.6$. Although the gap size is getting smaller when $f \approx 0.4$, it rises again after that. The energy will be emitted again after a peak. So, this condition can be used when the band energy which is needed is not from the first band.

IV. CONCLUSIONS

The wave expansion method has been successfully used to calculate the band gap structure of a metallic slab with air rods. We only used 121 waves to obtain a very accurate result. From this investigation, we find that the band energy, no matter what filling fraction, does not tend to zero at Γ. A 2D square lattice band gap appears in between the first and second band for all of the filling fractions. However, for the 2D triangular lattice, the band gap appears in between the second band and the third band, as well as the third and fourth band for f=0.4 and f= 0.5, respectively. Although the size of the gap is small, it still can be applied if the needed transmittal energy starts from the second band or third band. So, it can be used in different applications of metallic slabs. Our method of calculation can be extended to find the band gap structure of defect modes and waveguide modes of photonic crystals which are made of metallic slabs.

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