# Physical Parametric Analysis of the Terahertz Photonic Crystal Cavities Substrate Microstrip Antenna on the Performances

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*Abstract*—**In this paper, the photonic crystal cavity (PCC) as a substrate and microstrip patch antenna in Terahertz (THz) frequency has been simulated and analyzed. The objectives are to simulate and analyze the performances changes when the parameter of PCC and microstrip patch antenna are varied. THz PCC substrate microstrip antenna is a most simple way to generate THz frequency. However, they are limited studies that have been done in terms of its fundamental physical analysis. Therefore, this parametric analysis is proposed. The design of the PCC and rectangular microstrip patch antenna of the electromagnetic spectrum on the 2-D photonic crystal was simulated using Computer Simulation Technology (CST) CAD Package. The effective permittivity, 2.08 with host material PTFE and copper annealed at 0.6THz. We varies the radius of the via, thickness of PCC,spacing between via and the width of the PCC. For the patch antenna the thickness and the material are varied. The performances are monitored through its resonant frequency, S-parameter return loss (S11), Gain, Radiation pattern, E-field H-filed and current density.**

*Keywords*—**PCC, microstrip, material PTFE, CST CAD Package, Return Loss, effective permittivity, Gain, Radiation pattern, , E-field H-filed and current density**

## I. INTRODUCTION

Terahertz frequency (THz) band is coarsely defined as a portion of the electromagnetic spectrum which extends from 0.1 THz to 10 THz. Due to the unavailability of powerful sourecs, detectors and other hardware, this band has remained untouched by scientists and researchers for a long time being named as 'terahertz band gap'. In the last two decades, the semi-conductor technology has grown exponentially and its effect on the research in this band gap has also been noticed. With sustaining progress in terahertz research, various potential applications of this spectrum in this field of science and technology has been reported [1-3].. Interestingly, due to its unique position, as this band is situated between the two already explored regimes of the spectrums, it is possible to use electronic as well as photonic route to pave the way in the terahertz spectrum. On this way, the electronic and photonic routes are capable of exploring these components in the near microwave and far-infrared THz band, respectively [4]. Recently, Piesiewicz et al. [5] have shown the idea of gigabit indoor wireless communication in the band of 300 GHz, which would be reality in the feature. The THz sources, from optical techniques are quantum cascade laser (QCL) [6-8], lasers, and switching diode [9] and for the microwave techniques are microwave PCA [10]. The advantages of using microstrip techniques are the compactness and easy to fabricate. The current microwave with normal substrate, the antenna size would be bigger. In Terahertz the size of patch antenna can be very small but it is not easy to fabricate so that we suggest using the PCC as the substrate.

In this paper we suggest on using the photonic crystal cavity, PCC could be used to control the rate of spontaneous emission (lead the narrative to permittivity alteration, the higher effective permittivity the frequency will be decrease the frequency but higher thickness of the PCC. since they have ability of suppressing every mode in the structure for a given range of frequencies [11-12]. Besides, the researchers have used photonic crystal to enhance the electrical performance of microstrip antenna in microwave frequency regime [13-15].These crystals essentially 3-D dimensional dielectric mirrors, reflecting light along every direction in space.

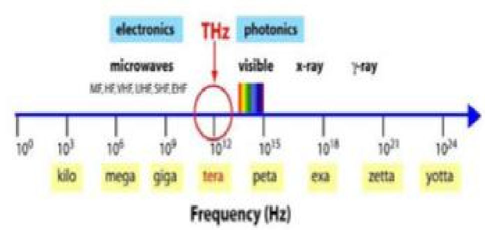



Figure 1: The position of THz band between microwave and far-infrared band.

## II. METHODOLOGY

### A. Design of photonic crystal cavity (PCC)

A 2-D photonic crystal of dimension *1000 X 1100* $\mu m^2$ is shown in Figure 1. In this structure, the air gaps of radius *10* $\mu m$ with periodicity of *100* $\mu m$ are placed along the *x axis*. The host material (PTFE) of dielectric constant, $\varepsilon_r$, 2.08 of thickness *200* $\mu m$ has been chosen. The boundary condition in z direction (top and bottom) has been set as periodic with zero phase shift and other sides have been kept open.

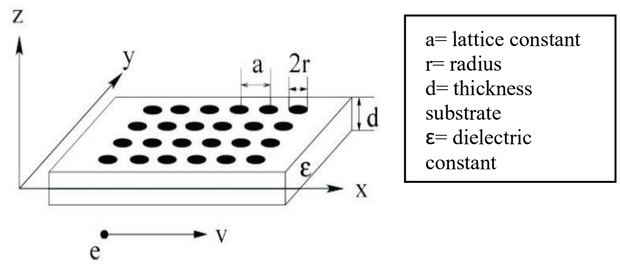



Figure 2: Dimension of photonic crystal cavity PCC

*B. Design of mcrostrip patch antenna*

The dimensions of the rectangular patch antenna have been calculated by following formulas:

$$W = \frac{c}{2f_o\sqrt{\frac{(\varepsilon_r+1)}{2}}} \tag{1}$$

$$\varepsilon_{eff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left[1+12\frac{h}{W}\right]^{-\frac{1}{2}} \tag{2}$$

$$L_{eff} = \frac{c}{2f_o\sqrt{\varepsilon_{eff}}} \tag{3}$$

W= width of patch
h= height of patch
c= speed of light
$\varepsilon_r$= relative permittivity
εeff= effective permittivity
$f_o$= operating frequency
$L_{eff}$= effective length

Based on formulas above, at 600 GHz width and length of antenna [16-19]. The *W= 298 µm* and *L=250 µm*. the designed. microstrip feed line also shown in the figure below.

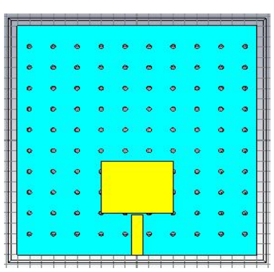


Figure 3: Schematic of the proposed antenna configuration.

To achieve better impedance match of the feed and resonator, the gap of microstrip feed-line technique has been used. The patch on the PTFE substrate has been fed by a microstrip transmission line width, *W= 50 µm* and length, *L= 193 µm* respectively. The gap between the feed-line and resonator is 7 *µm*. The return loss of proposed antenna is shown I figure below.

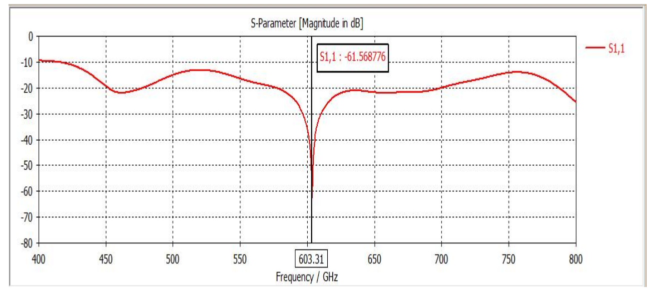



Figure 4: show a sharp resonance near 600GHz, based on the design as shown above.

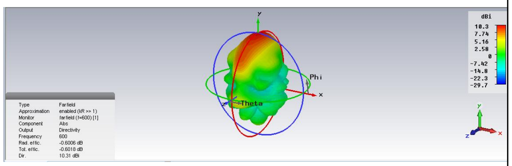
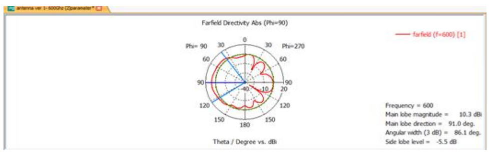
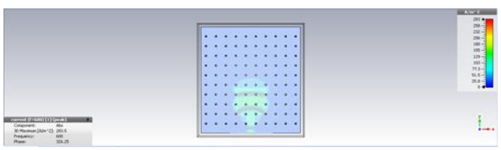
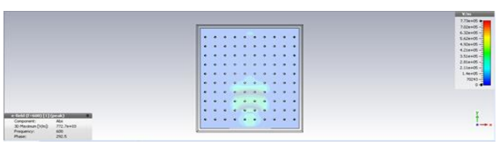
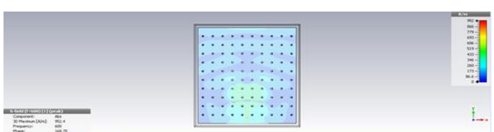
*C. Parameter study of the PCC and their performances*

The performances such as resonant frequency, return loss (S11) [20], gain, radiation pattern [21-23], E-field H-field[24] and current density can be monitored by varies the parameters. When one of the parameter the other parameters are fixed. Example varies the radius of the photonic crystal cavity PCC, while the others parameters thickness of substrate, spacing between via, width of substrate, thickness of patch and the material of the patch are fixed so that we can see what is the effect when varies on that parameter only.

Table 1: Parameter study of PCC and their performances

| Radius of via (µm) | Thickness of the substrate (µm) | Spacing between via (µm) | Width of substrate (µm) | Thickness of patch (µm) | Material of patch |
|---|---|---|---|---|---|
| 9.5 | 199.5 | 99.5 | 999 | 32.5 | Copper Annealed |
| 9.6 | 199.6 | 99.6 | 999.2 | 33.0 | Aluminum |
| 9.7 | 199.7 | 99.7 | 999.4 | 33.5 | Zinc |
| 9.8 | 199.8 | 99.8 | 999.6 | 34.0 | Brass (91%) |
| 9.9 | 199.9 | 99.9 | 999.8 | 34.5 | Gold |
| 10.0 | 200 | 100 | 1000 | 35.0 | Iron |
| 10.1 | 200.1 | 100.1 | 1000.2 | 35.5 | Chromium |
| 10.2 | 200.2 | 100.2 | 1000.4 | 36.0 | Copper |
| 10.3 | 200.3 | 100.3 | 1000.6 | 36.5 | Silver |
| 10.4 | 200.4 | 100.4 | 1000.8 | 37.0 | Nickel |
| 10.5 | 200.5 | 100.5 | 1001.0 | 37.5 | Magnesium |

Table 2: Radiation pattern, current density, E-field H-field distribution also shown its result

| Performances | Results |
|---|---|
| Radiation pattern |  (a)  Figure 1:(a) Radiation pattern in 3-Dimension (b) Radiation pattern in polar plot |
| Current density |  Figure 2:Current density |
| E-field |  Figure 3:E-field |
| H-field |  Figure 4:H-field |

## III. RESULTS AND DISCUSSION

### *A. Simulation Results*

#### 1) <u>**Parametric study varies in radius of the via**</u>

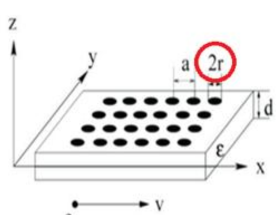



Figure 1: Radius of via

Table 1: Performance varies the radius of the via

| Radius of via (µm) | Frequency (GHz) | Return loss, s11 (dB) | Gain (dB) |
|---|---|---|---|
| 9.5 | 603.22 | -52.31 | 9.707 |
| 9.6 | 603.20 | -71.94 | 9.730 |
| 9.7 | 602.85 | -42.14 | 9.722 |
| 9.8 | 603.22 | -52.01 | 9.728 |
| 9.9 | 603.20 | -44.24 | 9.717 |
| 10.0 | 603.41 | -37.33 | 9.708 |
| 10.1 | 603.43 | -49.89 | 9.701 |
| 10.2 | 603.79 | -51.59 | 9.702 |
| 10.3 | 603.41 | -42.53 | 9.701 |
| 10.4 | 603.65 | -57.99 | 9.708 |
| 10.5 | 603.40 | -40.19 | 9.703 |

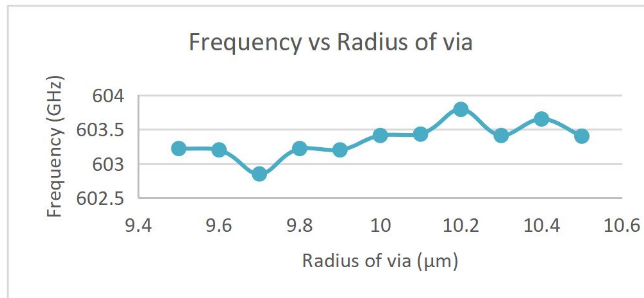



Figure 1.1: Frequency vs Radius of via

Based on the graph above shows that when varies the radius via of the photonic crystal cavity PCC the performance of the frequency does . The highest frequency is 603.8 GHz where the radius of the via holes increase to 10.2 µm from 10 µm. the defect of the via radius where r=0.1a so that the result show the frequency range are from 603.4 GHz to 603.8 GHz whereby when the r=0.09a the frequency will decrease from 603.4 GHz to 602.85 GHz. The higher the frequency more power will radiate.

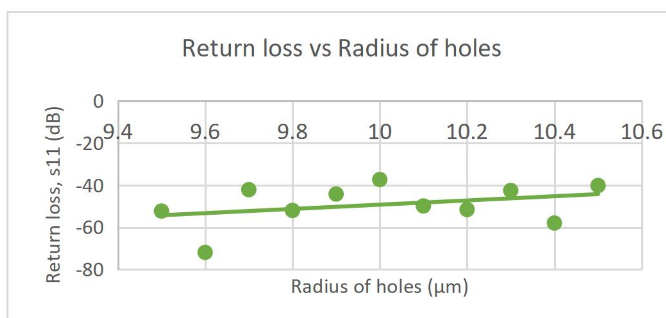



Figure 1.2: Return loss vs Radius of the holes

The lowest and the best return loss which is -71.94 dB when varies the radius of the via to 9.6 µm. From the result above, the performance of the return loss when varies the value via of the Photonic crystal cavity (PCC) are all below than -10 dB, so that the reflection loss is only a small value and the loss of the power is not too much because most power will be reflected.

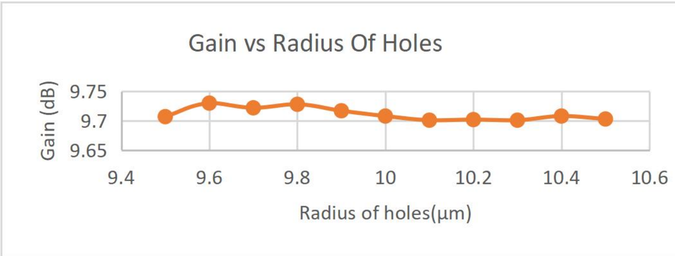



Figure 1.3: Gain vs Radius of holes

Based on the graph above show that the highest gain of the antenna which is 9.73 Db at radius of holes 9.6 µm and the lowest gain is at 10.3 µm which is 9.701 dB. The small the size hole of the PCC the high gain will consume to the antenna.

## 2) <u>Parametric study varies in thickness of the substrate/ PCC</u>

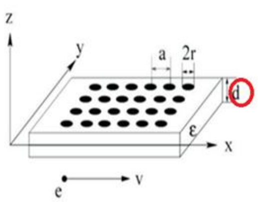



Figure 2: Thickness of substrate

Table 2: Performance varies the thickness of the substrate

| Thickness of the substrate (µm) | Frequency (GHz) | Return loss, s11 (dB) | Gain (dB) |
|---|---|---|---|
| 199.5 | 603.69 | -50.01 | 9.705 |
| 199.6 | 603.24 | -62.61 | 9.710 |
| 199.7 | 603.19 | -62.80 | 9.711 |
| 199.8 | 603.24 | -62.51 | 9.712 |
| 199.9 | 603.55 | -58.81 | 9.713 |
| 200 | 603.22 | -52.31 | 9.707 |
| 200.1 | 603.29 | -61.64 | 9.715 |
| 200.2 | 603.20 | -62.16 | 9.715 |
| 200.3 | 603.20 | -61.69 | 9.716 |
| 200.4 | 603.29 | -60.96 | 9.716 |
| 200.5 | 603.43 | -60.26 | 9.717 |

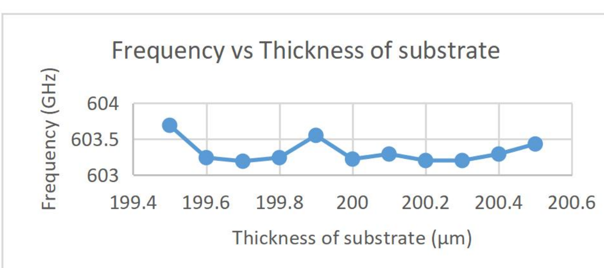



Figure 2.1: Frequency vs Thickness of substrate

As the previous research, the peaks shift to higher resonant frequencies (ωa/2πc) as the slab thickness decreases. Based on the graph above, when the substrate thickness at d=199.5 µm the frequency is at 603.7 GHz. Therefore the second highest of frequency is at thickness of substrate d=199.9 µm which is 603.55 GHz. The three lowest frequencies are at when d=1997 µm , d=200.2 µm and d=200.3 µm. at frequencies 603.19 GHz and 603.20 GHz. The thickness of a photonic crystal cavity on a slab significantly alters the emission wavelengths of the cavities mode. The shift in frequencies follows the shift of the photonic bandgap of the lattice.

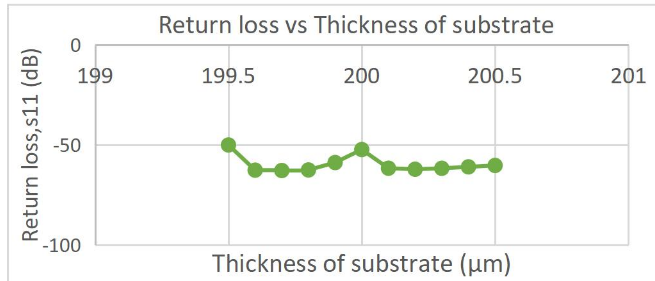



Figure 2.2: Return loss vs Thickness of substrate

The lowest and the best or the return loss which is -62.80 dB at the thickness of the substrate, d= 199.7 µm. While the highest of the return loss compared to other return loss changing in thickness substrate/slab of the PCC is -50.01 Db at d=199.5 µm.

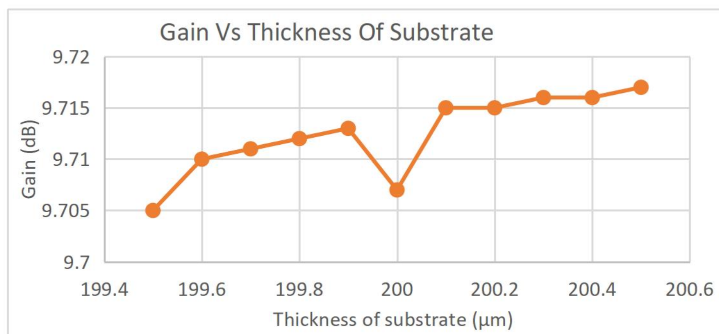



Figure 2.3: Gain vs Thickness of substrate

The gain are increasing as the thickness of the substrate PCC slab are increased. The gain also decreased when the thickness of the substrate are decreased. Based on the graph above, the highest gain is 9.717 dB at thickness of the substrate d= 2000.5 µm while the lowest gain is 9.705 dB at the thickness of the substrate d= 199.5 µm.

## 3) <u>Parametric study varies in spacing between via</u>

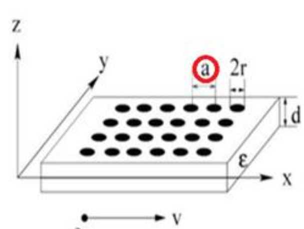



Figure 3: Spacing between via

Table 3: Performance varies the spacing between via

| Spacing between via (µm) | Frequency (GHz) | Return loss, s11 (dB) | Gain (dB) |
|---|---|---|---|
| 99.5 | 603.80 | -48.31 | 9.712 |
| 99.6 | 603.81 | -52.28 | 9.711 |
| 99.7 | 603.66 | -49.36 | 9.704 |
| 99.8 | 603.81 | -53.39 | 9.706 |
| 99.9 | 603.80 | -50.42 | 9.704 |
| 100 | 603.22 | -52.31 | 9.707 |
| 100.1 | 603.46 | -56.56 | 9.726 |
| 100.2 | 603.69 | -52.47 | 9.706 |
| 100.3 | 603.80 | -48.80 | 9.712 |
| 100.4 | 603.66 | -50.37 | 9.712 |
| 100.5 | 603.46 | -56.62 | 9.715 |

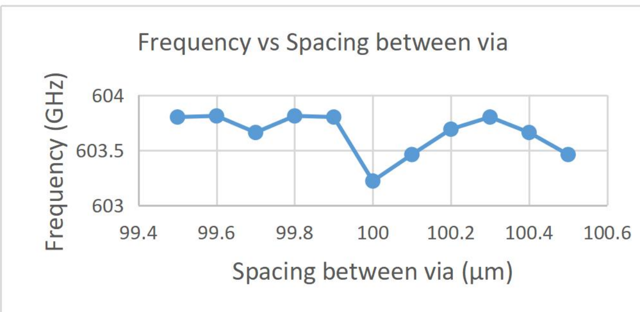



Figure 3.1: Frequency vs Spacing between via

Based on the result above show the frequency changing when varies the value of the spacing between via. If the value spacing between via is increased so that the frequency will be decreased while decreased the spacing between via the frequency will increased. The shape of the graph is depends of the formula f=ln $(1/a^2)$, a= 100.5 µm so that f=603.46 GHz. By increasing the lattice constant, a of the photonic crystal cavities the frequency can be shifted to lower frequency.

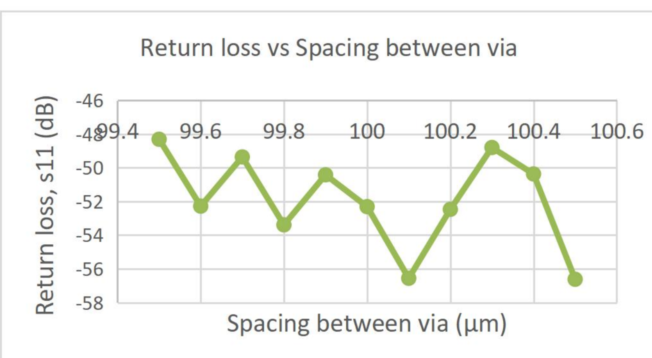



Figure 3.2: Return loss vs Spacing between via

The graph above show the performance when varies the parameter of spacing between via which is changing the spacing between via the result show the return loss for the antenna design. The bigger spacing between via the smaller the value of the return loss which is a= 100.5 µm so that the return loss is -56.62 dB. Besides, the smaller spacing between via the bigger the value of the return loss which 99.5 µm then the return loss is -48.31 dB. As conclusion the best result is the highest value of return loss when the lattice constant a=100.5µm.

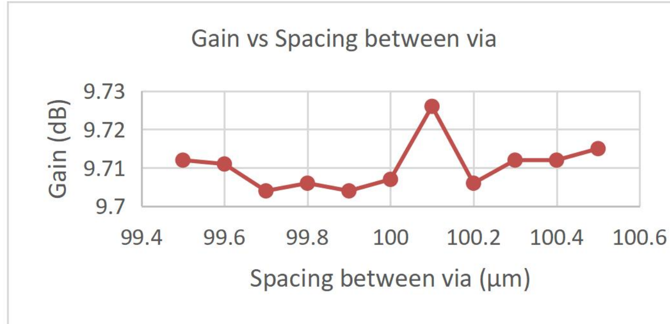



Figure 3.3: Gain vs Spacing between via

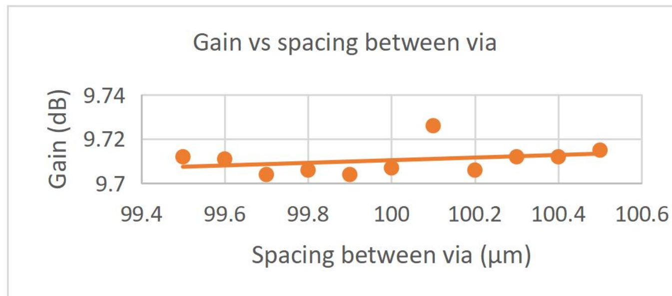



Figure 3.31: Gain vs Spacing between via

The differs of the parameter spacing between via does not affect too much on the gain based on the graph above. The highest gain is at the spacing between via, a= 100.5 µm which is 9.715 dB compared to the others distances of spacing between via the gain are range in between 9.715 dB to 9.7 dB. The higher the gain the more power will be consumed.

### 4) <u>Parametric study varies in width of substrate</u>

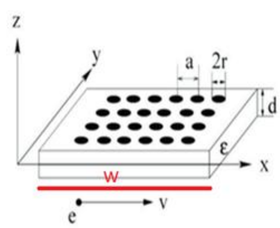
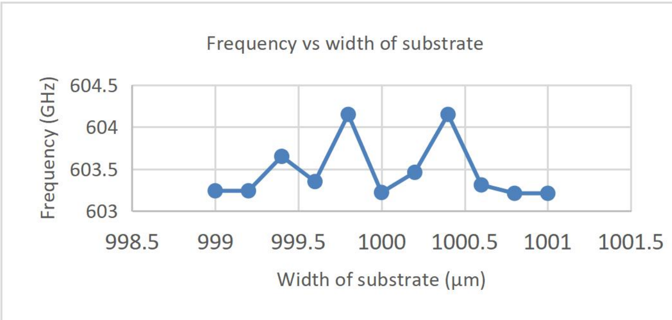



Figure 4: Width of substrate

Table 4: Performance varies the width of substrate

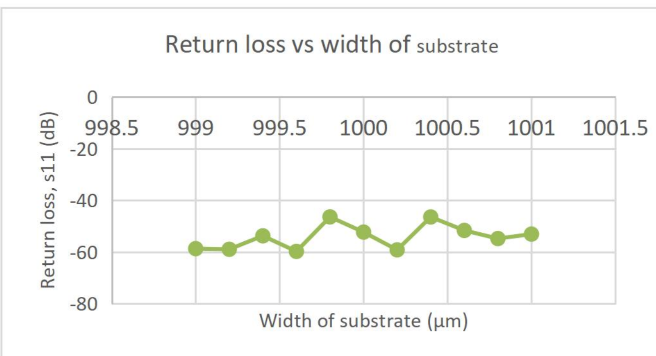
| Width of substrate (µm) | Frequency (GHz) | Return loss, s11 (dB) | Gain (dB) |
|---|---|---|---|
| 999 | 603.24 | -58.70 | 9.708 |
| 999.2 | 603.24 | -58.95 | 9.707 |
| 999.4 | 603.65 | -53.75 | 9.722 |
| 999.6 | 603.35 | -59.77 | 9.722 |
| 999.8 | 604.15 | -46.42 | 9.712 |
| 1000 | 603.22 | -52.31 | 9.707 |
| 1000.2 | 603.46 | -59.18 | 9.708 |
| 1000.4 | 604.15 | -46.45 | 9.707 |

| | | | |
|---|---|---|---|
| 1000.6 | 603.31 | -51.66 | 9.708 |
| 1000.8 | 603.21 | -54.80 | 9.709 |
| 1001.0 | 603.21 | -53.08 | 9.702 |



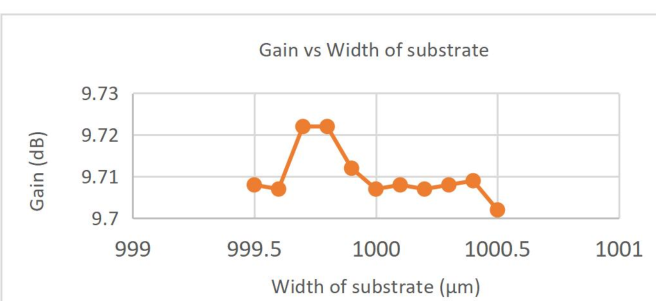

Graph 4.1: Frequency vs width of substrate

Based on the result above, when the width of the substrate is wider it show the lowest frequency which is w= 1001.0 µm and the frequency is 603.21 GHz. The highest the frequencies are f= 604.15 at width of the substrate w= 999.8 µm and w= 1000.4 µm.




Graph 4.2: Return loss vs width of substrate

The performance of return loss does not give effect too much when varying the width of the substrate photonic crystal cavity PCC. The range of return loss from -46.42 dB to -59.77 dB. The lowest return loss, s11 which is -59.77 dB at w=999.6 µm and the highest return loss, s11 is – 46.42 dB at w=999.8 µm. The average of the return loss is -52.31 dB where the width of substrate, w= 1000 µm.




Graph 4.3: Gain vs width of substrate

The graph above shows the wider of the width of the substrate the lowest gain while the narrower the width of the substrate photonic crystal cavity PCC the higher value of gain. This is because the power gain will be higher because the area of the substrate is smaller, area of substrate is when W x L where (W= width of substrate and L =length of the substrate). The highest gain when w= 999.4 µm and 999.6 µm which are 9.722 dB. The lowest gain is when w=1000.5 µm which is the gain 9.702 dB. The highest gain is the best compared to the others because more power will radiate.

## 5) <u>**Parametric study varies in thickness of patch antenna**</u>

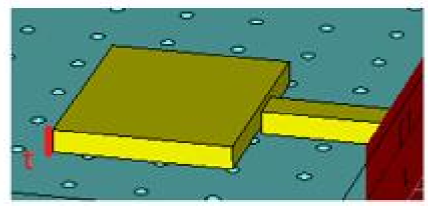



Figure 5:Thickness of patch

Table 5: Performance varies in thickness of patch

| Thickness of patch (µm) | Frequency (GHz) | Return loss, s11(dB) | Gain (dB) |
|---|---|---|---|
| 32.5 | 603.65 | -57.76 | 9.703 |
| 33.0 | 603.65 | -60.42 | 9.703 |
| 33.5 | 603.65 | -62.70 | 9.706 |
| 34.0 | 603.65 | -66.29 | 9.711 |
| 34.5 | 603.65 | -57.59 | 9.715 |
| 35.0 | 603.22 | -52.37 | 9.707 |
| 35.5 | 603.21 | -53.38 | 9.708 |
| 36.0 | 603.45 | -52.33 | 9.708 |
| 36.5 | 603.24 | -53.26 | 9.710 |
| 37.0 | 603.21 | -54.51 | 9.711 |
| 37.5 | 603.21 | -53.05 | 9.714 |

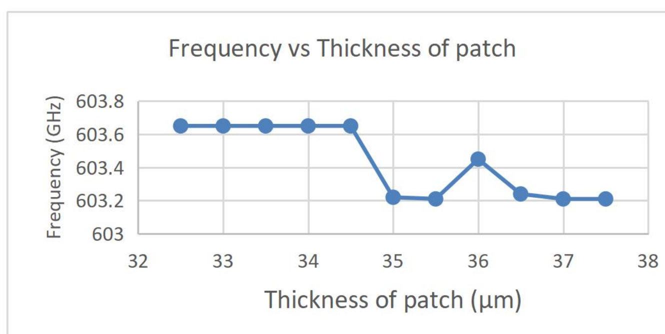



Figure 5.1: Frequency vs Thickness of patch

Based on the analysis of the previous research, with increasing substrate thickness of patch antenna (h)[25], the resonance frequency decreases. Based on the graph above, start from thickness of patch with 35µm to 37.5 µm the resonance frequency of each thickness is very low compared to thickness of patch with 35.5 µm to 32.5 µm the resonance frequency are very high which are 603.65 GHz.it is proven with the formula to calculate the effective dielectric constant $\epsilon\ reff = \frac{(\epsilon r+1)}{2} + \frac{(\epsilon r-1)}{2}\left[1+12\frac{h}{w}\right]^{-1/2}$ and the dimension of patch antenna $W = \frac{c}{2f_o\sqrt{\frac{(\varepsilon_r+1)}{2}}}$.

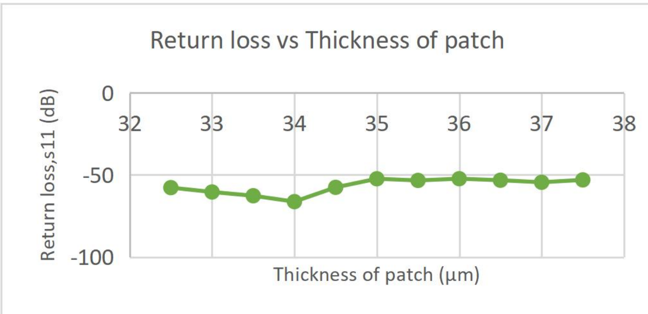



Figure 5.2: Return loss vs Thickness of patch

When the increasing the thickness of the patch antenna the changing of the return loss is decreased. The graph shows when varies the parameter thickness of patch so the result of return loss are between -52.33 dB to 54.51 dB. When decrease the thickness of patch the lowest return loss which is -66.29 Db. The best return loss is must upper than -10 Db, based on varying thickness of patch antenna all return loss are upper than -10 dB, but the best the result is when the return loss is – 66.29 dB compared to the other return loss.

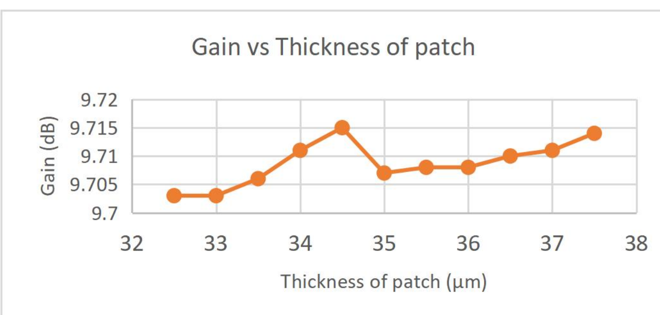



Figure 5.3: Gain vs Thickness of patch

The higher the thickness of the patch the higher the gain it will be. From the graph above, the thickness of patch increasing from 35 µm to 37.5 µm and also the gain will be increase 9.707 dB to 9.714 dB. When the thickness of the patch of antenna decrease from 35.5 µm to 32.5 µm the gain also decrease where the range are in between 9.715 dB to 9.703 dB. The highest gain is 9.715 dB at 34.4 µm in thickness of the patch compared to the other of thicknesses.it shows that the thickness of the patch antenna will affect the gain. If it is a patch antenna, increasing the substrate height could lead to gain enhancement. But the bandwidth would become smaller in this way. Also making antenna arrays is a way of increasing the overall gain.

## 6) Parametric study varies in material of substrates (patch)

Table 6: Performance varies in material of substrate

| Material of patch | Frequency (GHz) | Return loss, s11 (dB) | Gain (dB) |
|---|---|---|---|
| Copper Annealed | 603.22 | -52.31 | 9.707 |
| Aluminum | 603.56 | -52.06 | 9.706 |
| Zinc | 603.56 | -52.82 | 9.704 |
| Brass (91%) | 603.55 | -52.30 | 9.705 |
| Gold | 603.55 | -51.88 | 9.707 |
| Iron | 603.59 | -53.59 | 9.702 |
| Chromium | 603.59 | -54.06 | 9.700 |
| Copper | 603.46 | -59.81 | 9.714 |
| Silver | 603.29 | -62.01 | 9.714 |
| Nickel | 609.60 | -43.05 | 9.446 |
| Magnesium | 603.37 | -59.91 | 9.711 |

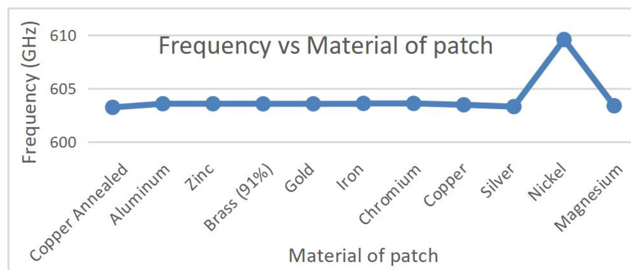



Figure 6.1: Frequency vs Material of substrate patch

The performance of the frequency does not give a lot of change too much when varies the material patch antenna. For the material of patch antenna such as copper annealed, aluminum, zinc, brass, gold, iron, chromium, copper, silver and magnesium the frequency range are only in between 603.22 GHz to 603.59 GHz. But for the nickel of material patch antenna the frequency is higher which 609.60 GHz. This is because when the permeability of that material is low so that the frequency will be high. Nickel is the best material compared to the others material that give the highest frequency.

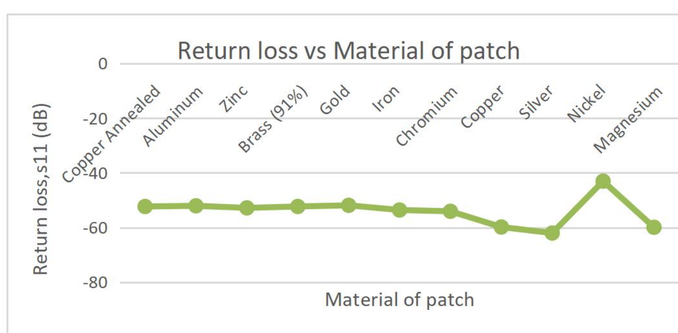


Figure 6.2: Return loss vs Material of substrate patch

For the return loss, s11 material of patch antenna like copper annealed, aluminum, zinc, brass, gold, iron, chromium, copper and magnesium also does not varies too much. But for the silver which is the lowest return loss -62.01 dB and the second highest is copper which is -59.81 dB . This is because silver and copper are the good conductor material. Unlike the material of nickel which is the lowest return loss compared the other materials -62.01 dB.

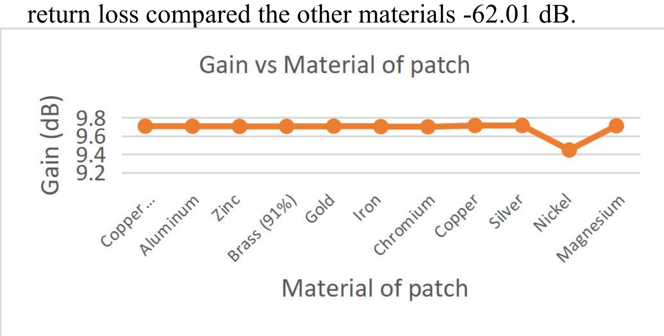



Figure 6.3: Gain vs Material of substrate patch

Based on the graph above, the performance of the gain is diverse with the performance of the return loss. This is means that the gain also depends on the return loss. When small return loss so that the energy trapped are less the gain will become smaller. For nickel material, the gain is only 9.446 dB where its return is -43.5 dB and for copper and silver both have the same gain which are 9.714 dB. Then the other materials the gain are around 9.7 dB above.

## IV. CONCLUSION

As a conclusion the physical parametric analysis of the terahetz photonic crystal cavities substrate microstrip patch antenna on the performances is presented in this paper. The proposed design antenna the PCC as a substrate microstrip antenna is a most simple way to generate THz frequency. The varies of parameter of photonic crystal cavity (radius of via, spacing between via, thickness of substrate and width of the substrate) and microstrip patch antenna (thickness of substrate and material of the substarte) effect on the performances of gain, radiation pattern, frequency, return loss, E-field H-field and current density. We can conclude that when varies the parameters of the photonic crystal cavity PCC and microstrip rectangular patch antenna the performances of the gain and the return loss are low return loss and higher gain. For the parameter of PCC is high thickness and spacing between via but for radius and width are small. While for the rectangular patch antenna high thickness and the material of patch is silver with the low return loss and high gain.

## V. REFERENCES

[1] P. H. Siegel, “THz instruments for space*,” IEEE Trans. Antennas Propag*, vol. 55, no. 11, pp. 2957-2965,2007.

[2] K. R. Jha and G. Singh, “Microstrip patch antenna on Photonic crystal substrate at terahertz frequency”, *IEEE technical paper*, 2009.

[3] M. S. Rabbani* and H. Ghafouri-Shiraz†, “improvement of microstrip antenna’s gain, bandwidth and fabrication tolerance at terahertz frequency bands”.

[4] R. Pieiewicz, M. Jacob, M. Koach, J. Schoebel and T. Kuner, “ Performance analysis of future multigigabit wireless communication systems and THz frequency with highly directive antennas indoor environments.” *IEEE Journal of Selected Topics in Quantum Electronics,* vol. 14, no. 2, pp. 421-430,2008.

[5] E. yablonovitch, J. Opt. Soc. Am. B 10, 283 (1993).

[6] J. Faist, F. Capasso, D. L. Sivco, C. Sirtori, A. L. Hutchinson and A. Y. Cho, “Quantum Cascade Laser”.

[7] J. Faist, C. Gmachl, F. Capasso, C. Sirtori, D. L. Sivco, J. N. Baillargeon and A. Y. Cho, “ Distributed feedback quantum cascade lasers”, *Appl. Phys*, 1997.

[8] R. Maulini, M. Beck and J. Faist, “ Broadband tuning of external cavity bound-to-continuum quantum-cascade lasers”, *Appl. Phys*, 2004.

[9] S.J.B.Yoo, “Advanced Optical Components for Next Generation Photonic Networks,” *Proc. SPIE* 5246, 224-234 2003.

[10] L. Min, “Novel materials, fabrication techniques and algorithms for microwave and THz components, systems and applications”, *Electrical engineering Electromagnetics Computer Science Nanotechnology*, 2016.

[11] P. R. Villeneuve and M. Piche, Prog. Quantum Electron. 18, 152 (1994).

[12] H. Y. D. Yang, N. G. Alexopoulos and E. Yablonovitch, “Photonic band-gap materials for high gain printed antennas,” *IEEE Trans. Antennas Propag*, vol. 45, no. 1, pp. 185-187, 1997.

[13] J. S. Colburn and Y. R. Samii, “Patch antennas on externally perforated high dielectric constant substrates,” *IEEE Trans. Antennas Propag*, vol. 47, no.12, 1785-1794, 1999.

[14] H. Boutayeb and T. A. Denidni, “Gain enhancement for mocrostrip patch antenna using a cylindrical electromagnetic crystals,” *IEEE Antennas Propag*, vol. 55, no. 11, pp. 3140-3144, 2007.

[15] D. M. Pozar, “Microwave Engineering*”, 4th ed., Jhon Wiley & sons inc*, 2012.

[16] A. Yadav, Dr. K. Pahwa, “ Design & prametric study of rectangular slot microstrip patch antenna for UWB applications” *IJEEE*, Vol. 1, Issue 3 (2014).

[17] R. A. Fayadh, H. A. Fadhil, F. Malek and N. Saudin, “ Design of ultra-wideband rectangular microstrip notched patch antenna”, *IEEE International Conference on Control System, Computing and Engineering*, 2013.

[18] N. Chakrabarti, S. Kalra, Mr. S. Saxena and Dr. M.R Tripathy, “Ultra-wideband antenna for a ground penetrating radar”, *IEEE*, 2016.

[19] S. S. Yavalkar, R. T. Dahatonde, Dr. S. S. Rathod and Dr. S. B. Deosrkar, " Parametric study for rectangular microstrip patch antennas", *IOSR Journal of Electronics and Communication Engineering (IOSR-JECE)*, Vol. 5, Issue 2, pp. 49-53, 2013.

[20] E. Bogatin, "How much return loss is too much?: Rule of Thumb #12", *EDN Network*, 2014.

[21] J. Huang, S. H. Kim and A. Scherer, "Design of a surface-emitting, subwavelength metal-clad disk laser in the visible spectrum*", Optics Express*, Vol.18, No. 19, 2010.

[22] H. M. Chen, Y. F. Lin, P. S. Cheng and P. S. Hall, " Parametric study on the characteristics of planar inverted-F antenna*", IEEE Proc. Micro, Antenna Propag*, Vol. 152, No. 6, December 2005.

[23] A. G. Derneryd, " A theoretical investigation of the rectangular microstrip antenna element", *IEEE Transactions on the antenna and propagation,* Vol. 26, N0. 4, 1978.

[24] Simulation of Photonic Crystal Cavities, *CST AG*, 2016.

[25] L. C. Paul, Md. S. Hosain, S. Sarkar, M. H. Prio, M. Morshed and A. K. Sarkar, "The effect of changing substrate material and thickness on the performance of inset feed microstrip patch antenna", *American Journal of Networks and Communications*, Vlo. 4, No. 3, pp. 54-58, 2015.