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Radiation Pattern Performance of Bow Tie Patch Antenna for Ground Penetrating Radar (GPR) Applications

(Prestasi Corak Sinaran Antena Tampalan Tali Leher untuk Aplikasi Radar Penembusan Tanah (GPR))

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ABSTRACT

This paper presents a directional bow tie patch antenna for ground penetrating radar (GPR) applications. There are four proposed designs for this paper. Three of the antenna is designed by introducing Sierpinski gasket fractal concept on bow tie patch antenna. There is some modification on this design in order to create a new different fractal design that is applicable for GPR applications. The bow tie antenna performance is studied across 1 GHz to 4 GHz. The best return loss obtained for this paper is at 3.7 GHz where all four designs have its best performance. The comparison at 3.7 GHz of these four antenna designs presented in this paper.

Keywords: Ground penetrating radar; bow tie antenna; patch antenna; radiation pattern

ABSTRAK

Makalah ini membentangkan antenna busur tampalan tali leher untuk aplikasi radar penembusan tanah (GPR). Terdapat empat rekabentuk yang dicadangkan dalam makalah ini. Tiga antenna dicadangkan dengan pengenalan kepada konsep fraktal gasket Sierpinski pada antena tampalan tali leher. Terdapat sedikit modifikasi kepada rekabentuk berkenaan untuk menghasilkan satu rekabentuk fraktal yang berlainan untuk digunakan dalam aplikasi GPR. Kajian berkenaan antena tali leher bermula pada 1 GHz sehingga 4 GHz. Pulangan terbaik yang diperolehi dalam makalah ini adalah pada 3.7 GHz dimana kesemua empat rekabentuk menghasilkan prestasi terbaik. Perbandingan dapa 3.7 GHz untuk keempat-empat rekabentuk antena akan dipersembahkan dalam makalah ini.

Kata kunci: Radar penembusan tanah; antena tali leher; antena tampalan; corak radiasi

INTRODUCTION

Ground-penetrating radar (GPR) is a geophysical technique that involves directing radar pulse signal to image the sub surfaces. This non-destructive method uses electromagnetic waves in the microwave band (UHF/VHF frequencies) of the radio spectrum from a transmitting antenna into the earth. GPR can detect the object that buried under the ground by radiating energy into the ground and detecting the echo signal or reflected signal from an object. The waves reflected when there is different permittivity of object and the medium (Harry 2008). The permittivity of an object can describe how polarizable it is. Different subsurface materials have well-known, characteristic, and contrasting permittivity. The reflected waves travel back to the surface where they are received and recorded by a receiving antenna. The depth and shape of the reflecting object and the information about the permittivity of materials can be determined (Harry 2008). GPR is used in a wide range of applications including evaluating concrete degradation, locating buried utilities, road construction, mapping pollutants, imaging archaeological features, detect leakage pipe, analysing karst hazards, and mapping geology.

Antenna is one of the most important part of a GPR system. The performance of the GPR system is depends on the performance of the antenna used for the system. It is because the antenna is the part in the system which transmit and receive electromagnetic waves. There are some of the general requirements that need to be considered before designing the antenna for the system. Firstly, the important factor that need to be considered is wideband operational antenna. It is because the wideband signal is used to provide resolution at centimetre size and able to locate even small objects (Karim et al. 2015). The wideband signal is to overcome the range-resolution problem that occurs in designing the antenna for GPR system. A lower frequency will result in higher penetration depth but a lower resolution. Meanwhile, higher frequency will provide a better resolution but the penetration depth will be lesser. Thus, lower frequency bands are used for deeper analysis and higher frequency band are used for detection smaller sub-surfaces objects or thinner layers located at shallow depth (Harry 2008). To benefit from both low and high frequencies, the wideband signal is used.

Furthermore, the antenna for GPR system needs to have high gain. This is due to the effect on directivity of the antenna. The higher gain provides higher directivity and it will affect the directivity of the radiation pattern which will be more directional (Balanis 2016). This directional antenna will radiate higher power in certain direction. Thus, the interference of noise or unwanted signal which comes from different direction will be reduced. Therefore, it is suitable for the antenna in GPR system due to the transmit signal are needed to direct toward underground than transmit or receive signal that propagate in free space. Another fundamental antenna parameter that needs to considered is bandwidth. From bandwidth, the range of frequency for the antenna to radiate or receive energy properly can be detected. From the range of frequency, the fractional bandwidth can be calculated whether it is wideband or narrowband antenna (Balanis 2016). To provide wideband antenna, large bandwidth is required.

The bow tie antenna is a combination of two imaginary triangle patch antenna which is designed on the single substrate. The bow tie patch antenna structure comes from biconical shape antenna. Because of biconical broadband characteristics, it has been used for VHF and UHF frequency for many years. However, there is a problem that occurs where the biconical structure is so massive in terms of size and causes the antenna to operate at VHF and UHF frequency and not practical. Due to its good radiation characteristics compared to other single antenna, the triangular structure and bow tie antenna were made and has been investigated experimentally by researcher to overcome the biconical problems (Rial et al. 2009). Biconic, bow-tie, and vivaldi antenna shapes demonstrated in Figure 1. The main features taken into consideration to select the most suitable antenna are the centre operating frequency of the antenna, gain, bandwidth, and also antenna size.

When central operating frequency is adjusted to minimum 1 GHz, biconic and Vivaldi antennas have to be quite large structures. It is shown that bow-tie antenna is the optimal antenna in terms of size, among mentioned antennas. However, when the mentioned antennas ere evaluated in terms of gaining, these antennas have points where their gaining's are sufficient in terms of their capacities. For the GPR application, bow tie antenna is determined to be the best suitable antenna type to be used in GPR system in terms of being light considering its design, being smaller when it is compared to other antenna types in constant frequency and in having higher gain and provide wide band signal (Rial et al. 2009).

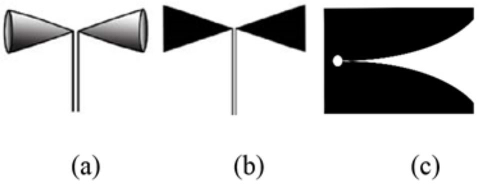


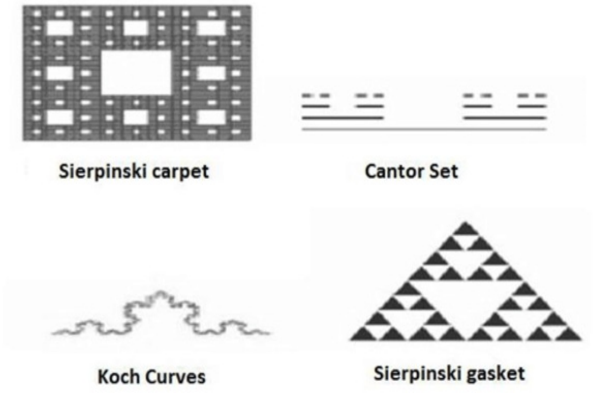
FIGURE 1. Example GPR antennas; (a) Biconic antenna, (b) Bow-tie antenna, (c) Vivaldi antenna

Bow tie antenna frequently used in GPR application due to many advantages that this antenna provides and it meets the requirement of antenna design for GPR system. The main advantages of bow tie antenna are directional radiation pattern, wideband signal, large bandwidth, and high gain. In this paper, the bow tie antenna design is chosen and will be used to design the antenna for GPR system.

Fractal antenna is an antenna with a self-similar design. This self-similar design is approximately similar to all part of itself which means some of the part have an equal shape as the entire object but on a different scale. This design is used in order to maximize the effective length of the antenna or to increase the perimeter of the antenna whether on inside sections or the outer structure. The radiation characteristic of any electromagnetic radiator or any antenna is depending on electrical length of the structure. Using the design of fractal geometry, we could increase the electrical length of the antenna while maintaining the same volume of the antenna. There are countless numbers of imaginable geometries that can be tried for designing a fractal antenna (Karamzadeh 2016).

One of the significant advantages of fractal antenna is that we acquire more than single resonant band or multiband. Furthermore, the fractal design theory can be used to reduce antenna size. The fractal design allows the antenna to reduce its size without any use of the components such as capacitor or inductor. This unique design can also be used to attain multiple bandwidth of the antenna and increase the bandwidth of each single band due to design with a self-similar geometry. Hence, this creates the fractal antenna design, an excellent choice to increase bandwidth of the antenna or to shrink the antenna size. Therefore, a good possible option for multiband and wideband applications is by using fractal antenna design (Jacques et al. 2012).

The fractal antenna is usually constructed with an iterative mathematical rule called Iterated Function System (IFS). This IFS is applied infinite number of times to create an ideal fractal shape design. The fractal geometry can take many different shapes such as Hilbert curve, Sierpinski gasket, and Koch curve as shown in Figure 2.



Sierpinski carpet

Cantor Set

Koch Curves

Sierpinski gasket

FIGURE 2. Example of fractal geometry

METHODOLOGY

An investigation of antenna criteria used in GPR system is needed before designing it. Generally, low frequency operation is required to have a good penetration of the signal but it will not produce small size antenna and high-resolution scanning. However, since the range of frequency of this project is 1 GHz to 4 GHz, thus the motivation to design a low frequency antenna for the required samples are to be investigated and analysed. Bow tie antenna is the most favoured type of antenna chosen by most researchers while doing GPR measurements. The reason includes its characteristics of having linear polarization, low directivity, and relatively limited bandwidth.

Figure 3 shows a sample of the rectangular patch antenna design. Based on the theory, rectangular patch antenna is designed by calculating the *W, εreff,* Δ*L*, and *L*.

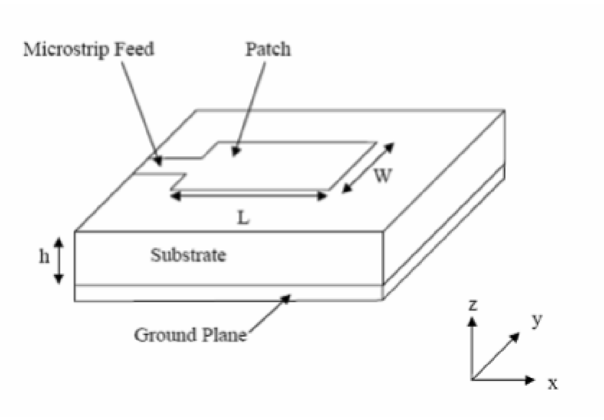


FIGURE 3. A schematic diagram of microstrip patch antenna

$$W = \frac{c}{2\,fr\sqrt{\frac{(\varepsilon r+1)}{2}}} \tag{1}$$

$$\varepsilon reff = \frac{\varepsilon r+1}{2} + \frac{\varepsilon r-1}{2}\sqrt{\left(1+12\frac{h}{W}\right)} \tag{2}$$

$$\Delta L = 0.412h\frac{(\varepsilon reff+0.3)\left(\frac{W}{h}+0.264\right)}{(\varepsilon reff-0.258)\left(\frac{W}{h}-0.8\right)} \tag{3}$$

$$L = \frac{c}{2fr\sqrt{\varepsilon reff}} - 2\Delta L \tag{4}$$

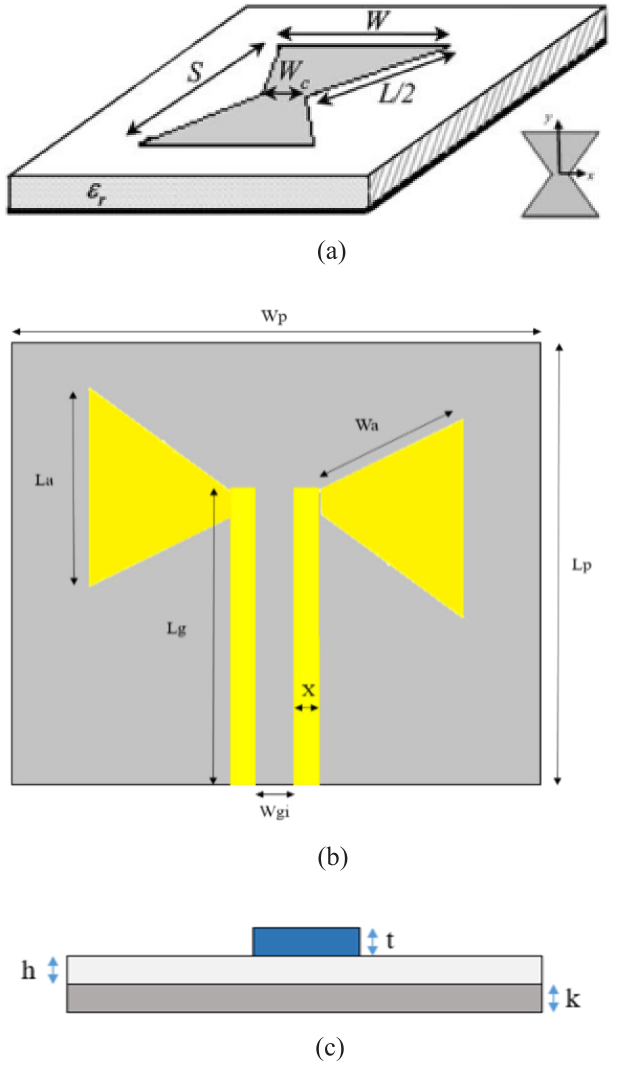
c = Speed of light in free space
εreff = Effective dielectric constant
εr = Dielectric constant of substrate
fr = resonant frequency
h = Height of substrate
W = Width of the patch
Δ*L* = Extended length

From the rectangular patch antenna formula, we can improve it and use as bow tie patch antenna formula.

$$W_c = W_b \tag{5}$$

W_b = width of the microstrip feed line
W_c = width of the center of bow tie patch antenna

The geometry of the antenna will be adjusted to get the frequency of this antenna to properly function in range between 1 GHz to 4 GHz. Antenna simulation were conducted after the design step have been calculated. The simulation was conducted by using CST software. CST is one of the accurate computational solutions for electromagnetic designs. With this software, the reflection coefficient, bandwidth, gain, and radiation pattern can be stimulating for further analysis. Figure 4 shows the schematic diagram of bow tie patch antenna that will be used in this research. This design is the result of improvising rectangular patch design and adding microstrip line.



(a)

(b)

(c)

FIGURE 4. Schematic diagram of bow tie patch antenna (a) 3D schematic, (b) above view and (c) side view

With *Wp* refers to width of substrate, *Lp* is length of substrate, *Wa* is the width of antenna, *La* refer to the length of antenna, *X* is the width of microstrip feed line, *Wgi* refers to the width of center of microstrip line, *h* is the height of substrate, *t* is referring to height of antenna and *k* is the height of ground plane.

For design 01 shown in Figure 5, a common bow tie patch antenna which is operated at frequency range within 1 GHz to 4 GHz is presented in this section. The antenna is designed by using Computer Simulation Technology software (CST). This design using an epoxy material which is FR4 with relative permittivity, *Er* = 4.3 as its substrate. The dimensions of the design 01 is shown in Table 1.

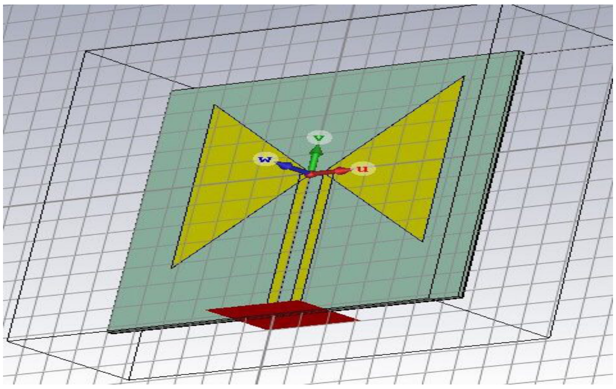


FIGURE 5. Design 01 for bow-tie patch antenna

TABLE 1. Parameter use in design 01

Parameter	Symbol	Design (mm)
Width of substrate	*Wp*	250
Length of substrate	*Lp*	250
Width of antenna	*Wa*	85
Length of antenna	*La*	85
Width of microstrip	*X*	15
Width of center of microstrip line	*Wgi*	9.5
Height of substrate	*H*	3
Height of antenna	*T*	0.03
Height of ground plane	*k*	1

Design 02 shown in Figure 5 hold a fractal bow tie patch antenna with some modifications. The geometry of the antenna from design 01 were improvised by doing iterative mathematical rule. This fractal geometry takes Sierpinski gasket concept and used two times iterations. However, the difference of this antenna compared to Sierpinski gasket concept is a triangle is added in the middle of the space after every iteration. For the first iteration, an inverted triangle is added in the middle of the space at each side of bow tie antenna. Meanwhile, six inverted triangles are added in the middle of the space for the second iteration. The whole dimensions for design 02 is shown in Table 2.

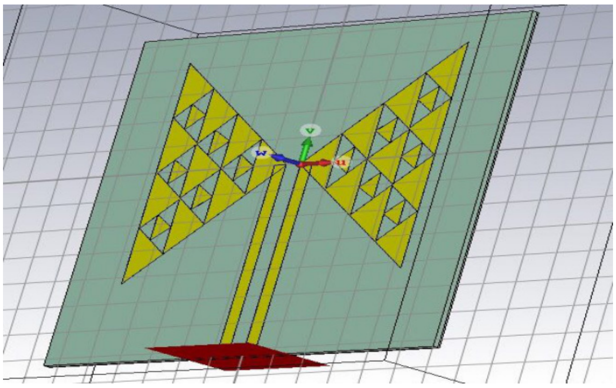


FIGURE 6. Design 02 for bow-tie patch antenna

TABLE 2. Parameter use in design 02

Parameter	Symbol	Design (mm)
Width of substrate	*Wp*	250
Length of substrate	*Lp*	250
Width of antenna	*Wa*	85
Length of antenna	*La*	85
Width of microstrip	*X*	15
Width of center of microstrip line	*Wgi*	9.5
Height of substrate	*H*	3
Height of antenna	*T*	0.03
Height of ground plane	*k*	1
Length of 1st iteration triangle	*Lk*	42
Length of 2nd iteration triangle	*La*	21

Figure 7 shows design 03, the design comes from the modification from design 02. The only difference between these two designs is there is no inverted triangle added at second iteration. The addition of inverted triangle is only once at the first iteration process. The dimensions for this design is shown in Table 3.

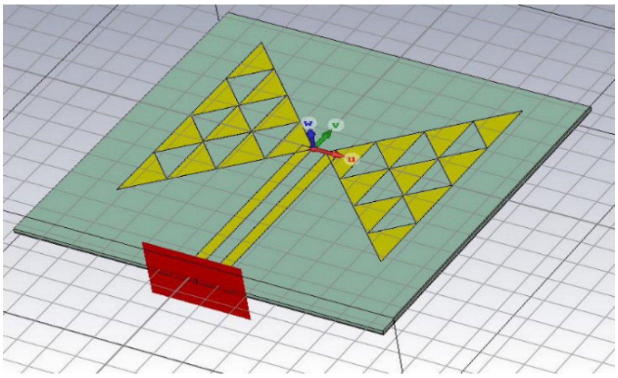


FIGURE 7. Design 03 for bow-tie patch antenna

TABLE 3. Parameter used in design 03

Parameter	Symbol	Design (mm)
Width of substrate	*Wp*	250
Length of substrate	*Lp*	250
Width of antenna	*Wa*	85
Length of antenna	*La*	85
Width of microstrip	*X*	15
Width of center of microstrip line	*Wgi*	9.5
Height of substrate	*H*	3
Height of antenna	*T*	0.03
Height of ground plane	*k*	1
Length of 1st iteration triangle	*Lk*	42
Length of 2nd iteration triangle	*La*	21

As for design 04 shown in Figure 8, it only applies Sierpinski gasket concept where two times iteration is done. The dimensions for design 04 is shown in Table 4.

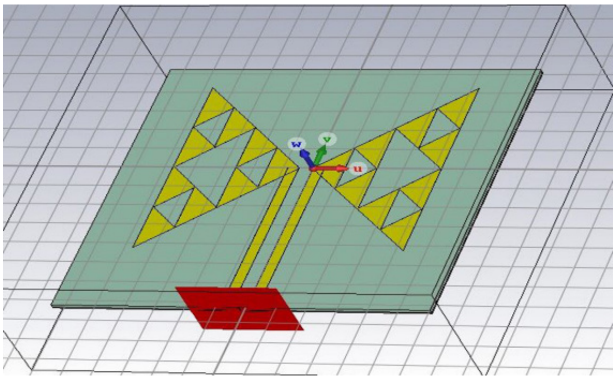


FIGURE 8. Design 04 for bow-tie patch antenna

TABLE 4. Parameter use in design 04

Parameter	Symbol	Design (mm)
Width of substrate	*Wp*	250
Length of substrate	*Lp*	250
Width of antenna	*Wa*	85
Length of antenna	*La*	85
Width of microstrip	*X*	15
Width of center of microstrip line	*Wgi*	9.5
Height of substrate	*H*	3
Height of antenna	*T*	0.03
Height of ground plane	*k*	1
Length of 1st iteration triangle	*Lk*	42
Length of 2nd iteration triangle	*La*	21

RESULTS AND DISCUSSION

S11 PARAMETER

S11 parameter, return loss, or reflection coefficient specifies the performance of the antenna. The frequency for the antenna to operate properly in terms of radiate and receiving can be located in S11 parameter chart. The return loss in the S11 parameter indicates power transferred from a port to another port which is from the transmitter to the receiving antenna. The antenna bandwidth can also be acquired from S11 parameter. The indication on the good antenna performance is the reflection coefficient must be on -10 dB or below. This is due to reflected power at -10 dB indicates that only 10% of the radiated power is reflected back or loss to surrounding which can be considered as small loss.

From Figure 9, all four designs operate within the range 1 GHz to 4 GHz are at its best performance around

3.7 GHz. Thus, further parameter comparison for these four designs can be proceeded at 3.7 GHz. Figure 9 shows that all the designs exceed -10 dB at 3.7 GHz which means the power reflected back or loss to surrounding from these design is less than 10% and more than 90% of its power is transmitted to the receiver. Furthermore, the bandwidth for design 01, 02, 03, and 04 are 40 MHz, 21 MHz, 87 MHz, and 110 MHz.

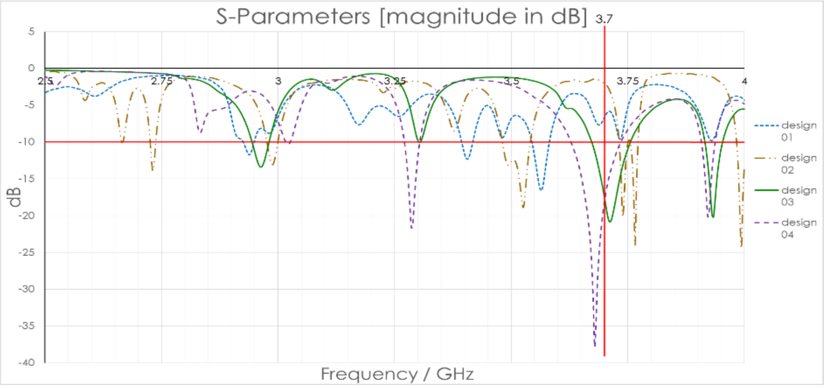
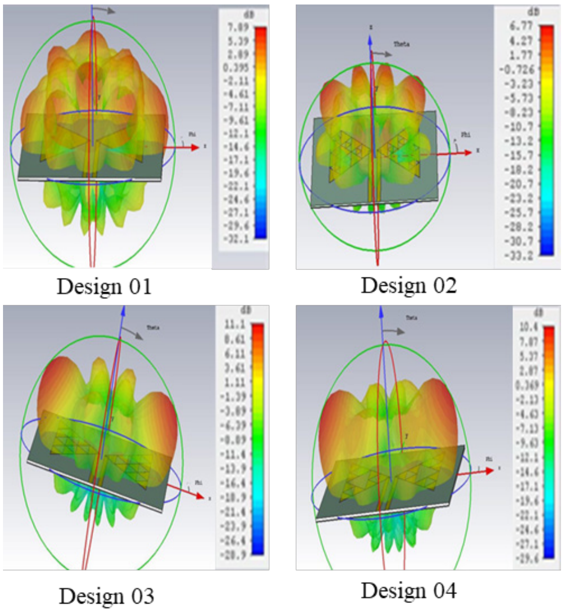


FIGURE 9. S11 parameter of all designs

GAIN

Gain can be described as performance that combines the directivity of the designed antenna and the efficiency of the designed antenna. From Figure 10, the gain from each design at 3.7 GHz is displayed. All these gains are at positive value which indicate all of these designs are radiate or operate properly.

As for the gain, the designed antenna requires to achieve value of gain that doubles the frequency value to be classified as high gain antenna. For these cases, all designs must achieve 7.4 dB in order to be categorized as high gain antenna. After examining the result, only design 02 cannot be considered as high gain antenna. Meanwhile, design 01, design 03, and design 04 is high gain antenna.


Design 01

Design 02

Design 03

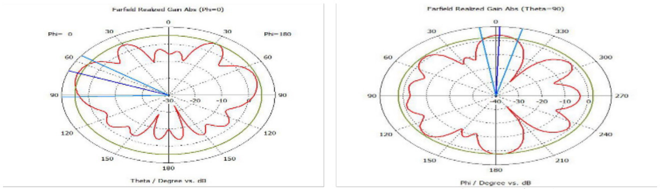
Design 04

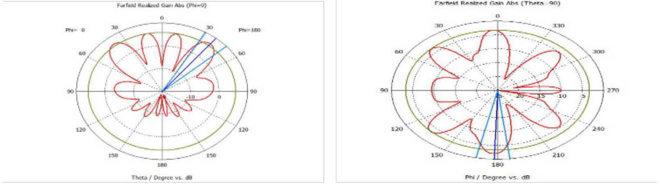
FIGURE 10. 3D radiation pattern of each design

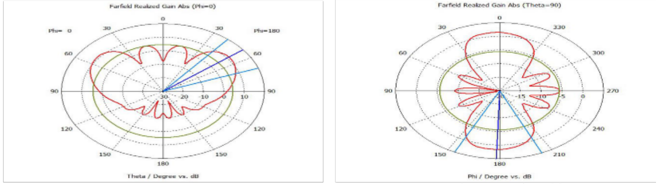
RADIATION PATTERN

Radiation pattern of designed antenna shows the radiation capabilities for the designed antenna. The radiation pattern of the bow tie patch antenna is presented in 2D form at 3.7 GHz operating frequency as in Figure 11.

From Figure 11, it shows that all these designs have directional radiation pattern. Directional radiation pattern is important for this project due to minimize the interference of noise or unwanted signal which comes from different directions. Moreover, the front-to-back ratio also can be obtained from Figure 16. Front-to-back ratio is the ratio of power gain between the front and back of a directional radiation pattern antenna. Usually, bigger front-to-back ratio indicates high performance antenna in term of directivity and gain. Front-to-back ratio for design 01, 02, 03, and 04 are 13.64 dB, 13.65 dB, 26.28 dB, and 22.48 dB, respectively.


E-plane Design 01 H-plane Design 01


E-plane Design 02 H-plane Design 02


E-plane Design 03 H-plane Design 03

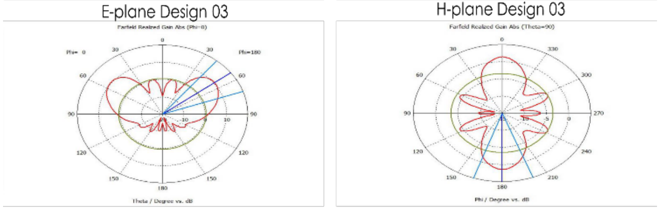

E-plane Design 04 H-plane Design 04

FIGURE 11. 2D radiation pattern for E and H plane

DISCUSSION

The result from the simulation of designed antenna has been analysed and recorded as in Table 5. From the range of frequency targeted, the best performance of antenna to operate is around

3.7 GHz. Hence, the comparison of the results is evaluated at 3.7 GHz. In terms of gain, design 03 and design 04 are suitable for GPR application. Even though design 01 can be considered as high gain antenna, it gains only slightly exceeds the requirement of high gain antenna.

As for GPR application, it needs high gain to radiate higher power in certain direction in order to penetrate underground medium. As for bandwidth of the antenna, the bigger the bandwidth result in better resolution for GPR application. However, bandwidth is not a very important parameter that needs to be considered in designing antenna compared to other parameters. This is because GPR application depends more on its signal strength, radiation, and interference issues.

For S11 parameter, -10 dB is the common value to indicate either the antenna operates successfully or not. The antenna operates properly as long it achieves -10 dB and below. As for this project, all the design radiates properly and the most less reflected power is design 04 with 0.017% only.

As for front-to-back ratio, the value is taken from the higher gain lobe and its gain in direction of 180° from the specified azimuth. The higher front-to-back ratio indicates the higher the directivity of the antenna. For this parameter, the highest value is obtained by design 03.

TABLE 5. Result for each design

Parameter	Gain (dB)	Bandwidth (MHz)	S11 parameter (dB)	Front-to-back ratio (dB)
Design 01	7.89	40	-16.571	13.64
Design 02	6.77	21	-23.998	13.65
Design 03	11.1	87	-20.853	26.28
Design 04	10.4	110	-37.727	22.48

CONCLUSION

Outcomes from the research shows that design 03 is the best choice compared to the other designs. This design achieves the highest gain compared to others which is 11.1 dB and gain is a very important parameter in GPR applications. Furthermore, design 03 also achieved highest front-to-back ratio 26.28 dB which indicates it is the best directional radiation pattern. Moreover, this design can be considered as small antenna. In terms of bandwidth and S11 parameter, design 03 did not get the highest result compared to others but the result can be considered as suitable for GPR applications

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DECLARATION OF COMPETING INTEREST

None

REFERENCES

Balanis, C.A. 2016. *Antenna Theory: Analysis and Design.* 4th edition. Hoboken: John Wiley & Sons, Inc.

Harry, M.J. 2008. *Ground Penetrating Radar Theory and Applications*. Amsterdam: Elsevier.

Jacques, L., Vehel, C.T. & Evelyne, L. 2012. *Fractals in Engineering: From Theory to Industrial Applications.* Springer Science & Business Media.

Karamzadeh, S., Kilic, O.F., Hepbicer, A.S. & Demirbas, F. 2016. Semi-fractal bow tie antenna design for GPR applications.

Karim, M.N.A., Malek, M.F., Ibrahim, S.Z. & Jamlos, M.F. 2015. High gain wideband transceiver antenna for ground penetrating radar applications. *I4CT 2015 - 2015 2nd International Conference on Computer, Communications, and Control Technology, Art Proceeding.*

Rial, F.I., Lorenzo, H., Pereira, M. & Armesto, J. 2009. Analysis of the emitted wavelet of high-resolution bowtie GPR antennas. *Sensors* 9(6): 4230-4246.