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Gain And Front To Back Ratio Improvement Of UWB Bowtie Antenna Using Reflectors For Ground Penetrating Radar Applications

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Abstract

The gain and front to back ratio of UWB bowtie antenna is improved in this paper to meet the requirements of Ground Penetrating Radar (GPR) applications. GPR antennas must have good gain toward the ground to achieve more ability of penetration, and high front to back (F/B) ratio to save the power and reduce external electromagnetic interferences. This is done by adding planar and parabolic reflectors to the proposed antenna, which has fractional bandwidth (FBW) of 138% within (1-5.45) GHz. The simulation has been carried out using CST Microwave Studio to study the effect of each reflector on the gain and F/B ratio. Toward the ground, planar reflector achieves maximum gain improvement of 4.75 dB, and maximum F/B ratio of 14 dB with bandwidth (1-2) GHz only. So, it cannot change the general behavior of main antenna gain. While parabolic reflector achieves maximum gain improvement of 35.35 dB, maximum F/B ratio of 33.79 dB over the whole bandwidth, and FBW of 156% within bandwidth (0.92-7.44) GHz. According to these results antenna with parabolic reflector is fabricated, and the gain and return loss is measured. The measurements show a good agreement with the simulation results.

Keywords: Bowtie Antenna, Antenna Gain, Front To Back Ratio, Planar Reflector, Parabolic Reflector.

تحسين الربح ونسبة الحزمة الإشعاعية الأمامية إلى الخلفية لهوائي ربطة العنق فائق المجال الترددي باستخدام العواكس لتطبيقات سبر أعماق الأرض

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الملخص

تم في هذه المقالة تحسين الربح ونسبة الحزمة الإشعاعية الأمامية إلى الخلفية F/B لهوائي ربطة العنق فائق المجال الترددي لتلبية متطلبات تطبيقات رادار سبر أعماق الأرض GPR. يجب أن تتمتع هذه الهوائيات بربح جيد باتجاه الأرض لتحقيق مزيد من القدرة على الاختراق، وكذلك نسبة F/B عالية لتوفير الطاقة وتقليل التداخلات الكهرطيسية الخارجية. تم ذلك عن طريق إضافة عواكس مستوية وقطع مكافئ للهوائي المقترح والذي يبلغ عرض مجاله الترددي الكسري 138% ضمن المجال GHz (1-5.45). تم إجراء المحاكاة باستخدام برنامج CST Microwave Studio لدراسة تأثير كل عاكس على تحسين الربح ونسبة F/B. حقق العاكس المستوي تحسيناً أعظمياً في الربح باتجاه الأرض بمقدار 4.75 dB، وقيمة أعظمية لنسبة F/B بمقدار 14 dB وذلك ضمن المجال الترددي GHz (1-2) فقط، فلم يتمكن من تغيير السلوك العام لربح الهوائي الأساسي. بينما حقق عاكس القطع المكافئ تحسيناً أعظمياً في الربح باتجاه الأرض بمقدار 35.35 dB، وقيمة أعظمية لنسبة F/B بمقدار 33.79 dB وذلك ضمن كامل المجال الترددي للهوائي الذي أصبح عرض مجاله الترددي الكسري 156% ضمن المجال GHz (0.92-7.44). بناء على هذه النتائج تم تصنيع الهوائي وإضافة عاكس القطع الزائد، وتم قياس الربح باتجاه الأرض وعامل الانعكاس، وأظهرت نتائج القياسات تطابقاً جيداً مع نتائج المحاكاة.

الكلمات المفتاحية: هوائي ربطة العنق، ربح الهوائيات، نسبة الحزمة الإشعاعية الأمامية إلى الخلفية، العاكس المستوي، عاكس القطع المكافئ.

1. INTRODUCTION

Ground Penetrating Radar systems are used as effective tools to detect subsurface targets by transmitting and receiving electromagnetic waves, which penetrate through the propagation medium (different types of soil, water, ice, asphalt ....etc). Reflected signals from the targets can be processed to obtain a radargram that gives information about detected targets such as depth and location.

In Ground Penetrating Radar (GPR) Systems, radar equation (1) defines all parameters that affect the performance of underground target detection [1,2].

$$\frac{P_r}{P_t} = e_t\,(1-|\Gamma_t|^2)\,D_t(\theta,\phi)\,\frac{e^{-2\alpha R_1}}{4\pi R_1^2}\,\sigma \times \frac{e^{-2\alpha R_2}}{4\pi R_2^2}\,e_r\,(1-|\Gamma_r|^2)\,D_r(\theta,\phi)\,\frac{\lambda^2}{4\pi} \quad (1)$$

Where:

Pt, Pr: Transmitted & received signals.

et, er: Radiation efficiency of transmitter and receiver antennas.

Γ_t, Γ_r: Reflection Coefficient of transmitter and receiver antennas.

$\sigma\ or\ RCS$: Radar cross section.

$D_t(\theta,\phi)$, $D_r(\theta,\phi)$: Directivity of the transmitter and receiver antennas.

α: Attenuation Factor.

R1, R2: Target distances far from transmitter and receiver antennas.

$e^{-2\alpha R_1}, e^{-2\alpha R_2}$: Soil absorption in the two ways.

$\frac{1}{{R_1}^2}$, $\frac{1}{{R_2}^2}$: Spreading loss in the two ways.

λ: Wavelength.

GPR antennas have strict requirements such as a fractional bandwidth greater than 100%, high gain 5-12 dB over the bandwidth toward the propagation medium (ground in general) to provide more penetration, and unidirectional beam that means greater front to back (F/B) ratio [3] to reduce electromagnetic interferences.

From radar equation, one can notice that transmitter and receiver anten have a large effect on target detection performance through the Gain, which is given by:

$$\mathrm{G}(\theta,\emptyset) = \mathrm{e}\,(1-|\Gamma|^2)\,D(\theta,\emptyset) \qquad (2)$$

Accordingly, antenna gain must be enhanced to increase the received signal power and target depth.

Researches have presented many ways to increase the gain of antennas such as adding planar reflectors [3,4], planar reflectors with slots [5], metamaterial surfaces [6], frequency selective surface FSS layers [7], corner reflectors [8], cube or cavity reflectors [9,10] and parabolic reflectors [11,12].

In this paper, UWB Bowtie antenna is designed and two methods are presented to enhance its gain toward the ground and F/B ratio by adding planar or parabolic reflectors to it. The two methods are simulated by CST software and the results is compared to show their effect on antenna gain and F/B ratio to meet GPR requirements. UWB bowtie antenna with parabolic reflector is fabricated and measured and the measurement results confirmed its superiority over the planar reflector for GPR applications.

2. PROPOSED ANTENNA

UWB Bowtie Antenna is designed to achieve ultra-wide frequency range (1-5.45) GHz for return loss values ($S_{11} \leq -10$ dB). This frequency range meets a fractional bandwidth of 138% that is suitable for antenna work in GPR applications, as it achieves one of the important requirements of GPR antennas. This importance comes to achieve two important goals. The first goal is to use lower frequencies to achieve greater penetrating depth as larger wavelengths have less attenuation in the propagation medium. The maximum depth according to [13] is 20λ. Therefore, proposed antenna achieves maximum depth 6 m at frequency 1 GHz. The second goal is to use higher frequencies to achieve better resolution between adjacent targets, which is around 1λ [13]. Therefore, proposed antenna achieves resolution 0.3 m at frequency 1 GHz, and 0.05 m at frequency 5.45 GHz.

To achieve this large bandwidth, bowtie antenna has been design with two corner bended triangular arms in antipodal technique, two triangular slots, tapered feeder network, and FR4 substrate with dielectric constant ($\mathcal{E}_r$=4.3), thickness (h=1.6 mm) and loss tangent (δ=0.025). The shape and dimensions of proposed antenna are shown in Figure 1. The antenna design in detail can be found in [14].

Using CST Microwave Studio simulation software, the bowtie antenna gain is simulated over the bandwidth (1-5.45) GHz towards the ground (ϴ = 0°, Ø = 0°) to find out the compatibility with GPR applications as shown in Figure 2.

The bowtie antenna achieves acceptable values of gain toward the ground (1.6-3.7) dB within the bandwidth (1-1.8) GHz. The maximum value of the gain is 3.7 dB at the frequency 1.5 GHz. The values of the gain start to decline after frequency 1.8 GHz, meaning that the rest frequency range is not suitable for use in GPR applications.

The radiation pattern of the bowtie antenna symmetrically radiates in two directions (0°,180°). This is normal in Bowtie antennas as it is similar to the dipole antenna, but this bidirectional radiation is not desirable for GPR applications, which require unidirectional radiation toward the ground. Therefore, F/B ratio must be obtained as much as possible to save the power and reduce the effect of electromagnetic interference from the external medium.

To solve these two problems, two suitable planar and parabolic reflectors will be added to the proposed antenna in order to enhance the gain values toward the ground and obtain a unidirectional radiation pattern.

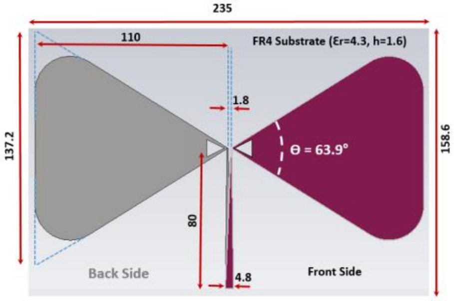

Figure (1) Proposed antenna with dimensions in mm

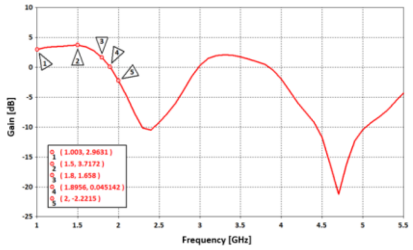

Figure (2) Proposed antenna broadband gain over the bandwidth (ϴ = 0°, Ø = 0°)

3. GAIN IMPROVEMENT USING PLANAR REFLECTOR

In this method, a planar copper reflector is used at a distance Z from the antenna, as shown in Figure 3, with a thickness of 1 mm and the same length and width as the antenna substrate. The mathematical model for this case has been studied in detail in [1,3] based on Image Theory, where an imaginary antenna is formed on the opposite side of the reflector as shown in Figure 4, that enhances the radiated power toward the ground.

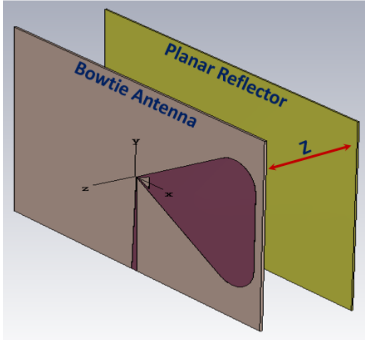

Figure (3) Antenna with planar reflector configuration

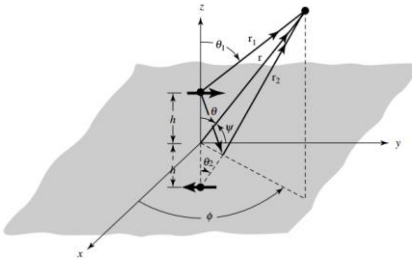

Figure (4) Radiation by image theory using infinite, flat and perfect conductor

Direct and reflected electric field Ed, Er are given by [1]:

$$E_d = j\eta \frac{kI_0 l e^{-jkr_1}}{4\pi r_1} \sin\psi \qquad (3)$$

$$E_r = -j\eta \frac{kI_0 l e^{-jkr_2}}{4\pi r_2} \sin\psi \qquad (4)$$

And the total electric field E is given by:

$$E = j\eta \frac{kI_0 l e^{-jkr}}{4\pi r} \sqrt{1 - \sin^2\theta \, \sin^2\phi} \times [2j \sin(kz\cos\theta)] \qquad (5)$$

The optimal Z value is determined by broadband gain simulation over the bandwidth for several values of 50, 60, 70, 80 mm as shown in Figure 5. At first glance, Z = 50 mm is the best for improving the gain, but actually it has a bad effect on S_{11} values as shown in Figure 6.

At Z=50 mm the bandwidth starts from 1.1 GHz at $S_{11} \leq -10$ dB values instead of 1 GHz. This is logical and expected because the value of Z is directly proportional to a quarter of the wavelength λ/4 depending on equation (5). Therefore, a decrease in distance between antenna and planar reflector will be associated with an increase in the frequency. Then, Z=60 mm is the optimum value, as the antenna keeps the bandwidth constant and achieves a gain range (0.93-8.43) dB within the frequency range (1-2) GHz.

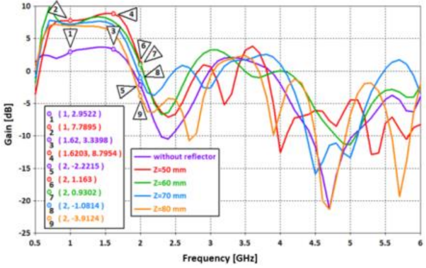

Figure (5) Gain of antenna with planar reflector for several values of (Z) at (Ɵ = 0°, Ø = 0°)

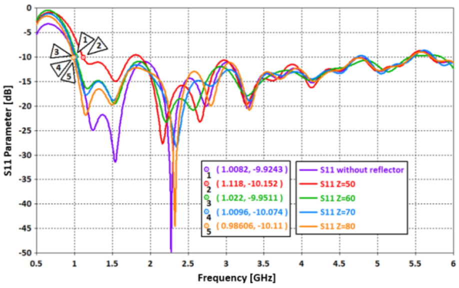

Figure (6) Return loss of antenna with planar reflector for several values of (Z)

4. GAIN IMPROVEMENT USING PARABOLIC REFLECTOR

In this method, a parabolic reflector is used, as shown in Figure 7 with a thickness of 1 mm, diameter D=400 mm, and depth H_0=87 mm, so the focal length is F=115 mm according to the mathematical model as shown in Figure 8 [1].

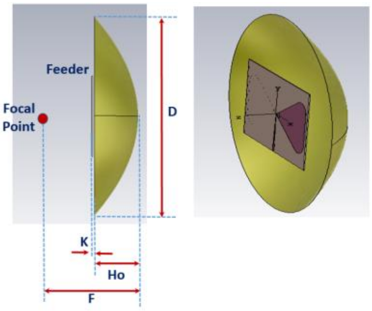

Figure (7) Antenna with parabolic reflector configuration

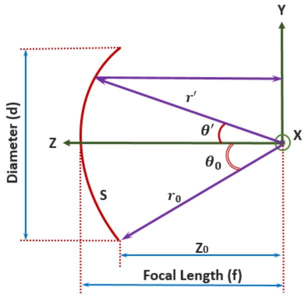

Figure (8) Configuration of Parabolic Reflector

Focal length F is given by:

$$F = \frac{D^2}{16\, H_0} \qquad (6)$$

The angle Ɵ0 is calculated by:

$$\theta_0 = \tan^{-1} \left| \frac{\frac{D}{2}}{f - \frac{D^2}{16\, f}} \right| \qquad (7)$$

Parabolic reflector antenna directivity is determined by:

$$D_0 = \left(\frac{\pi D}{\lambda}\right)^2 \left\{ \cot^2\left(\frac{\theta_0}{2}\right) \left| \int_0^{\theta_0} \sqrt{G_f(\theta')} \tan\left(\frac{\theta'}{2}\right) d\theta' \right|^2 \right\} \qquad (8)$$

The optimum distance of the parabolic reflector from the antenna K is chosen using the simulation results of the gain over the bandwidth for several values K=28, 23, 18, 10, 5, 0 mm as shown in

Figure 9. This optimization is very important to reduce spillover radiation at parabolic edges.

The distance K=0 mm achieves the best gain at the bandwidth (1-3) GHz, but it is the worst at bandwidth (3-6) GHz. The optimum value with the greatest stability of the gain values over the bandwidth is K=5 mm. Its gain values fluctuate around the average value of 13.5 dB.

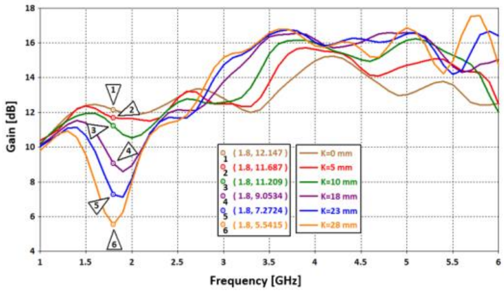

Figure (9) Gain of antenna with parabolic reflector for several values of (K)

at (Θ = 0°, Ø = 0°)

5. RESULTS AND DISCUSSION

The gain of the UWB Bowtie Antenna has been improved using planar and parabolic reflectors. Figure 10 shows the gain simulation results toward the ground with and without reflectors. Clearly, it can be seen that the parabolic reflector is superior to the planar reflector for GPR applications in four important points: Firstly, planar reflector cannot change the general behavior of main antenna gain, while parabolic reflector can do that. Secondly, parabolic reflector has greater gain improvement. It achieves a maximum gain of 15.71 dB at the frequency 3.9 GHz, while the planar reflector achieves a maximum gain of 8.43 dB at the frequency 1.4 GHz. The maximum gain of the proposed antenna is 3.71 dB at the frequency 1.5 GHz. Thirdly, parabolic reflector has better gain stability, while planar reflector has big difference in gain values when the frequency changes. Finally, parabolic reflector has acceptable gain over the bandwidth (1-5.45) GHz, which is better for GPR applications, while planar reflector cannot exceed the frequency 2 GHz that decreases GPR ability to detect small-sized targets and distinguish between adjacent targets which is 0.15 m.

The maximum gain improvement is 4.75 dB using planar reflector, and 35.35 dB using parabolic reflector at 4.7 GHz. The maximum F/B ratio is 14 dB with planar reflector, while it is 33.8 dB with parabolic reflector at 1 GHz. Therefore, parabolic reflector is better to use for GPR application in the presence of electromagnetic interference. In addition, it saves power supplied from batteries that means longer work hours.

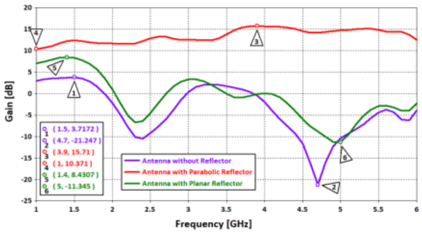

Figure (10) Simulation results of the gain of antennas with and without reflectors

Figure 11 shows the 2D-radiation pattern of the antenna in its three states at the frequency of 1.5 GHz. It shows the effect of the two reflectors on reducing the back lobe. It shows that parabolic reflector is better than planar reflector because it achieves greater values of F/B ratio.

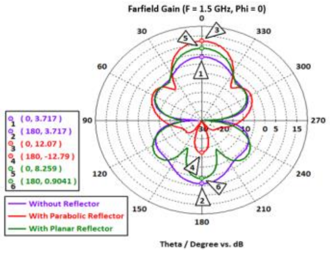

Figure (11) 2D Radiation pattern for antenna with and without reflectors at F=1.5 GHz

Front to back ratio at frequency 1.5 GHz is 7.36 dB for planar reflector, and 24.86 dB for parabolic reflector, while it is 0 dB for antenna without reflectors.

Figure 12 & 13 show the radiation pattern of parabolic reflector antenna where front, back and side lobs are clearly appeared. Table 1 summarizes F/B ratios for all frequencies depends on front and back lobs. In GPR applications, the larger Beamwidth the better clarity of detection in the radar image. Therefore, the side lobs within ±50° will become a positive point that can be used as an essential part of the main beam.

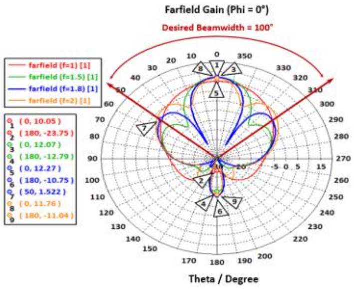

Figure (12) Parabolic reflector antenna radiation patterns for 1-2 GHz

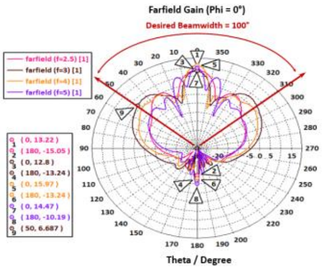

Figure (13) Parabolic reflector antenna radiation patterns for 2.5-5 GHz

Table (1) Front to Back Ratios for parabolic reflector antenna

F [GHz]	1	1.5	1.8	2	2.5	3	4	5
FBR [dB]	33.8	24.86	23	22.8	28.27	26	29.2	24.66

Because of its good performance, parabolic reflector antenna has been fabricated as shown in Figure 14. The gain has been measured using three reference antennas at L,S and C bands, microwave generator (Aeroflex IFR 6813A 10 MHz-20 GHz), and spectrum analyzer (Rohde & Schwarz FSH20 9 KHz-20 GHz). Figure 15 shows a good agreement between simulation and measured gain results.

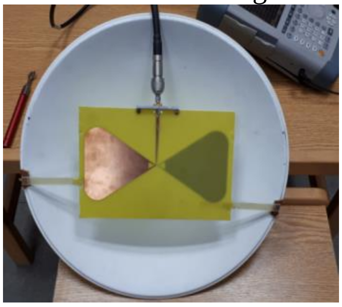

Figure (14) Fabricated antenna with parabolic reflector

The return loss has been simulated using CST software and measured using Rohde & Schwarz vector network analyzer. Figure 16 shows an increasing of bandwidth simulation results (0.92-7.44) GHz with FBW=156%, and increasing of bandwidth measurements results (0.92-6.9) GHz with FBW=153%. The reason behind that depending on [15] is the air gap between the main substrate and reflector that act as a dielectric substrate with $\varepsilon_r = 1$. This will reduce the total permittivity and increase the bandwidth.

Table 2 presents a comparison of the results of this work with the previous works that used various methods to improve the gain of antennas. It shows that the parabolic reflector outperforms all other reflectors in achieving a high value for antenna gain so it is widely used in many applications.

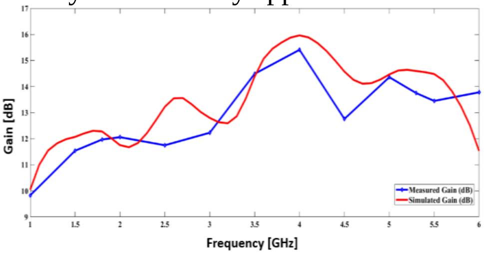

Figure (15) Simulated and measured gain results for antenna with parabolic reflector

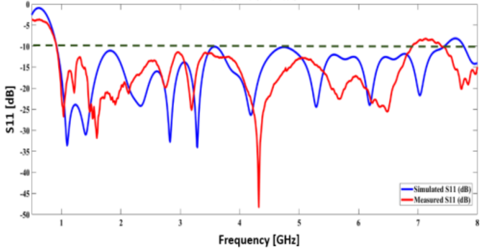

Figure (16) Measured and simulation return loss for antenna with parabolic reflector

Table (2) Comparison between previous works & this work

Reference	Year	Design	Frequency [GHz]	Peak Gain [dB]
[3]	2019	Planar Reflector	0.64 - 2	1 – 5.1
[5]	2021	Slotted Planar Reflector	0.6 – 4.6	2 - 7
[6]	2018	Meta-material Planar Ref.	0.5 – 1.2	4 - 9
[7]	2019	FSS Reflector	3.1 – 10.6	6.5 - 9
[9]	2015	Metal Cavity & Absorber	1.4 – 3.5	6
[10]	2018	Hollow Cube Reflector	0.98 – 4.5	7.5 – 10.3
[11]	2020	Parabolic Reflector (Diameter 2.5 m)	4.148	31.1
[12]	2016	Printed Parabolic Reflector	2.25 – 2.63	10.3
This Work	2022	Planar Reflector	1 – 2	0.93 – 8.43
This Work	2022	Parabolic Reflector (Diameter 0.4 m)	0.92 – 7.44	9.9 – 15.71

6. CONCLUSION

Planar or Parabolic reflectors have been added to UWB bowtie antenna after designing it. The aim was increasing the gain and front to back ratio to make it suitable for Ground Penetrating Radar applications. These two procedures has been simulated by CST software. The simulation results have shown that good gain and F/B ratio using planar reflector within bandwidth (1-2) GHz were achieved, while parabolic reflector has achieved better gain and F/B ratio within bandwidth (0.92-7.44) GHz that will increase penetrating depth and resolution for GPR systems. Parabolic antenna was fabricated and measured and a good agreement between measured and simulated results was achieved.

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