A Novel Wideband VHF Antenna for Impulse Ground Penetrating Radar Systems

Dong Tan Phuoc[1], Pham Minh Quang[2], Bui Huu Phu[1], and Lai Nguyen Duy[3]

[1] DCSELAB, University of Technology, Vietnam National University in Hochiminh City, Vietnam
[2] Post and Telecommunication Institute of Technology, Vietnam
[3] Hochiminh City University of Transport, Vietnam
`bhphu@dcselab.edu.vn`

Abstract. In this paper, we propose a novel wideband VHF antenna operating at central frequency of 200 MHz for impulse ground penetrating radar (GPR) systems. As operating at the low frequency, impulse GPR systems can work well at the depth to 5 m. The proposed bow-tie antenna has been created based on the Lemniscate curve. This structure helps the antenna achieve better performance than conventional bow-tie antennas. In the paper, we also propose a wideband balanced-to-unbalanced (balun) transformation line to feed our antenna. The balun has good performance and matching impedance. The antenna is implemented in FR4 substrate and copper patch. Based on design, simulation, and implementation results, it has been shown that our proposed antenna has a good matched impedance, stable radiation patterns, and constant gain. Thus, it can be thoroughly applied to GPR systems in the future.

Keywords: ground penetrating radar (GPR), wideband antenna, Lemniscate curve, bow-tie antenna.

1 Introduction

Ground penetrating radar (GPR) technology has been widely studied over the world. The GPR system emits electromagnetic energy into ground and receives reflection signals to process and display images of objects underground. The technology can be applied to variety of fields such as military, constructions, geophysics, etc [1]. One important component in any GPR system is the transmit and receive antennas [2]. Antennas for GPR system should be designed to radiate pulses with given properties into the ground and receive reflected signals from subsurface objects as in [3].

The penetration depth of impulse GPR system is limited by the electrical conductivity of the ground, the radiated power, and the transmitted central frequency. The lower the operation frequency is, the deeper the signals can be penetrated, but the less the resolution of the systems has. So, antennas of GPR systems are required carefully in design to have as low central frequency and high bandwidth as possible for applications which require consideration in depth [4-14].

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Recently, many studies on improving the deeper penetration for impulse GPR systems have been considered. Authors in [4] have proposed the GPR antenna suitable above dry sand with relative dielectric permittivity in the frequency range from 500 MHz to 3 GHz with a small conductivity. The antenna has a broadband, thus give GPR systems to have a high resolution. However, the UHF central frequency of this antenna does not improve the range of depth for the GPR systems. Authors in [5] have designed a loaded antenna operating in the frequency band from 0 to 300 MHz. However, the voltage standing wave ratio (VSWR) of the antenna is less than 2.5 and makes difficult in signal processing at the receiver. Authors in [6] have studied a shielded antenna for GPR systems. Although it has a good transmit signal with shielding and absorbing materials, their designed antenna is used in a GPR system working at 400MHz central frequency, and could not penetrate deeper than 3 m.

In this paper, we propose a novel wideband VHF antenna to improve the deep penetration for impulse GPR systems. Unlike above bowtie antennas, our antenna is based on Lemniscate curves to achieve a better radiation and smaller size. We also propose a broadband balun matching with the proposed antenna. The proposed antenna can work well in the bandwidth from 176 MHz to 232 MHz, and make GPR systems receive reflected signals at the depth to 5 m.

The remaining of the paper is as follows. Our proposed antenna and balun are presented in detail in Section 1. The simulation results is also shown in this section. In Section 3, the implementation and measurement results of the antenna have been provided. Finally, the conclusions are included in Section 4.

2 Proposed Wideband Antenna

The proposed antenna is designed based on FR4 dielectric substrate and copper patch for impulse GPR systems. We use the Lemniscate curve to create the structure of the antenna. This curve of the patch of antenna is shown in Fig. 1. The locus of the point P on the Lemniscate curve can be determined from two focal points F and F' such that 2OF.OF' = a^2 (where a is the distance from O to the center focal point F). The equation of Lemniscate curve in Cartesean coordinate is shown as followings [7]:

$$(x^2+y^2)^2-2a^2(\mathrm{x}^2-\mathrm{y}^2)=0 \tag{1}$$

and the form in plolar coordinate is given by:

$$r^2=2a^2\cos(2\theta) \tag{2}$$

The curve Lemniscate of the designed antenna has length La = 541.3 mm, width Wa = 182 mm, and the gap between the two wings of the antenna is 5 mm, as shown in Fig. 2.

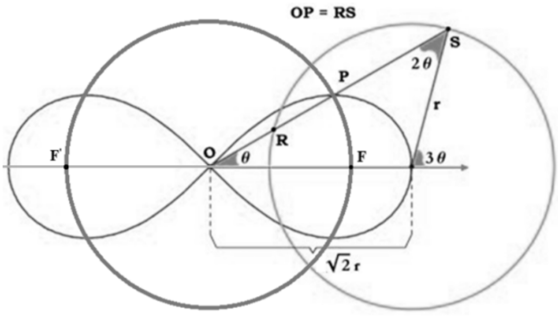


Fig. 1. The Lemniscate curve

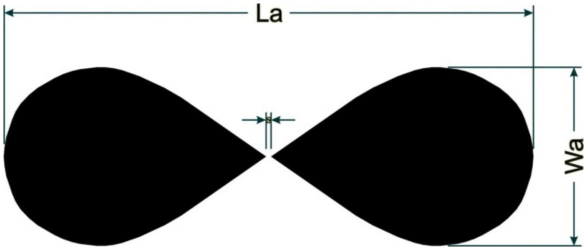


Fig. 2. Geometry and configuration of the proposed antenna

The distance of Lemniscate curve for this antenna is designed $\sqrt{2}r = 268.15$ mm and OF = 186.61 mm. Like the dipole antenna, the feed line of the Lemniscate antenna is located in middle of the wings at S opened point. Proposed antenna is designed by using FR4 dielectric material has a length Ls is 546.3 mm, width Ws is 192 mm, the thickness of FR4 dielectric substrate h is 1.6 mm, dielectric constant εr is 4.6, loss tangent tan δ is 0.02, and the thickness of the copper patch t of 35 μm, as shown in Fig. 3.

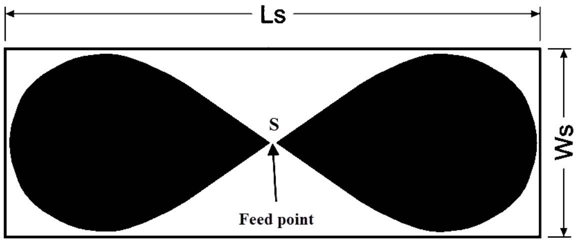


Fig. 3. Geometry and configuration of the proposed antenna

The proposed microstrip taper balun is designed to transform from the unbalanced structure of the coaxial cable 50 Ω impedance to the antenna structure balance in the 200 MHz frequency is shown in Fig. 4. This taper-line balun has two sections: the balanced line portion which matches the antenna impedance to 50 ohm and a portion which actually performs the mode transduction. The dimensions of the balun are shown in Fig. 5 and its values is shown in Table 1.

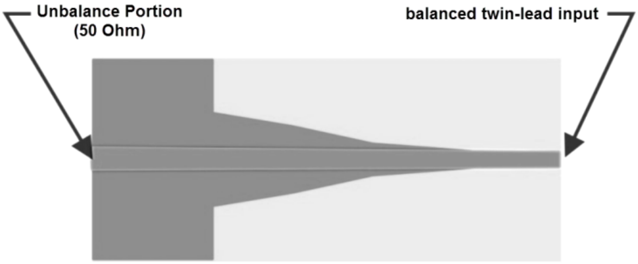
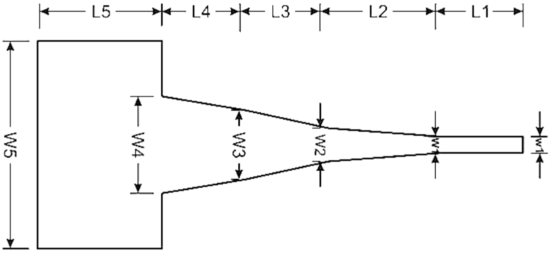
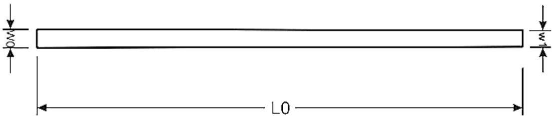


Fig. 4. Configuration of the microstip taper balun



Bottom Plane



Top Plane

Fig. 5. The dimensions of balun

Table 1. The Dimension Values of Balun

n	W_n (mm)	L_n (mm)
0	3	300
1	3	60
2	6	90
3	12	60
4	25	60
5	40	30

Firstly, we simulate our proposed antenna without the balun. The value of reflection coefficient S11 is equal to - 21.1 dB at the central frequency of 200 MHz, and S11 is less than - 10 dB and VSWR is less than 2 in the frequency range from 184.38 MHz to 221.6 MHz, as shown in Figs. 6 and 7. Input impedance of the designed antenna Z = 42.52 + 3.24*j Ω at frequency 200 MHz. The real part and the imaginary part of the impedance respectively is presented in Figs. 8 and 9.

Secondly, we connect our proposed balun to the designed antenna to make a good match impedance and increase performance of antenna, as shown in Fig. 10. The simulation results of the antenna with balun is shown in Figs. 11 and 12.

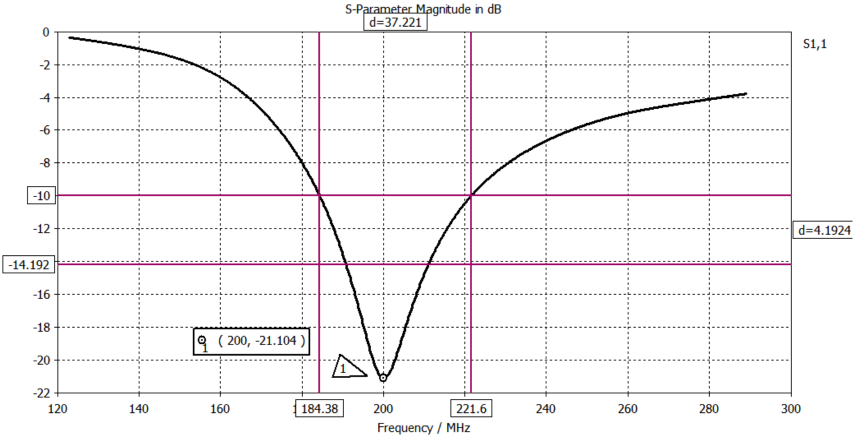


Fig. 6. Return loss S11 of the antenna without balun

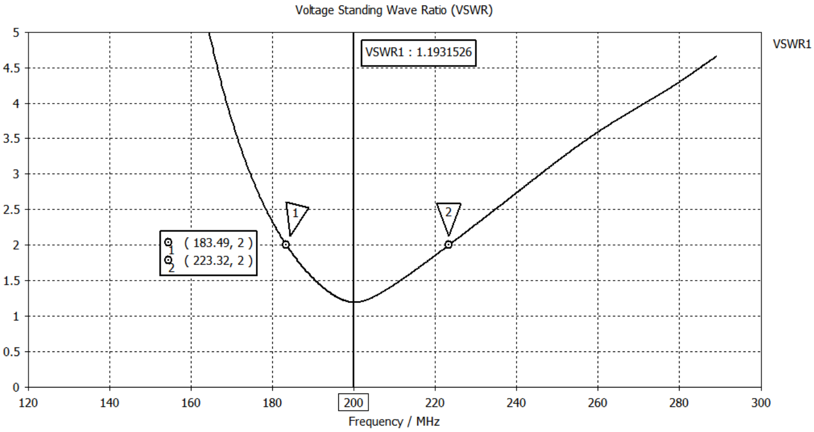


Fig. 7. VSWR of the antenna without balun

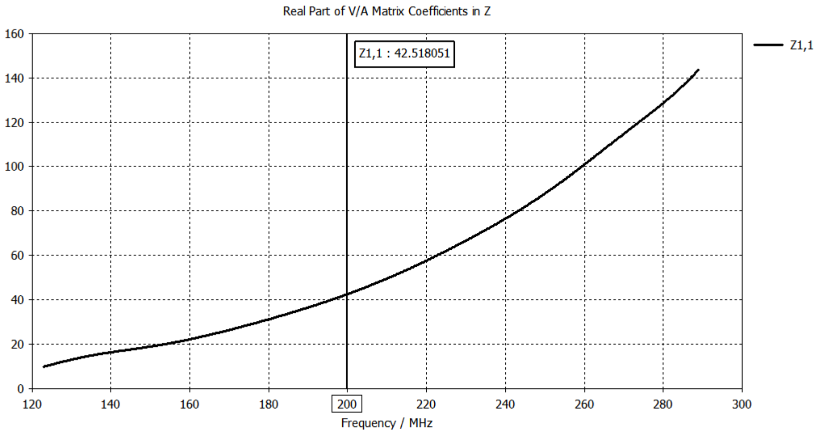


Fig. 8. The real part of the impedance

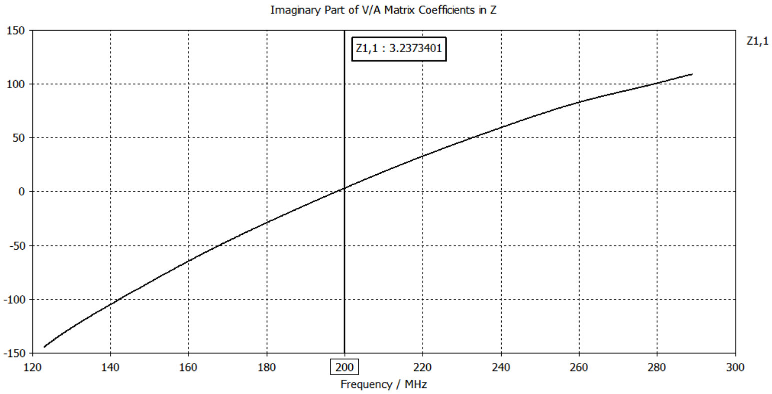


Fig. 9. The imaginary part of the impedance

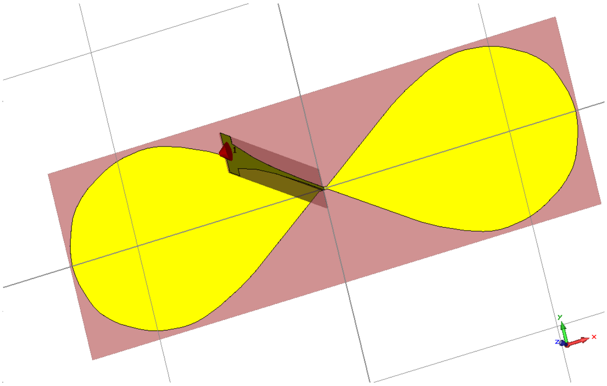


Fig. 10. Antenna with balun in simulation environment of CST software

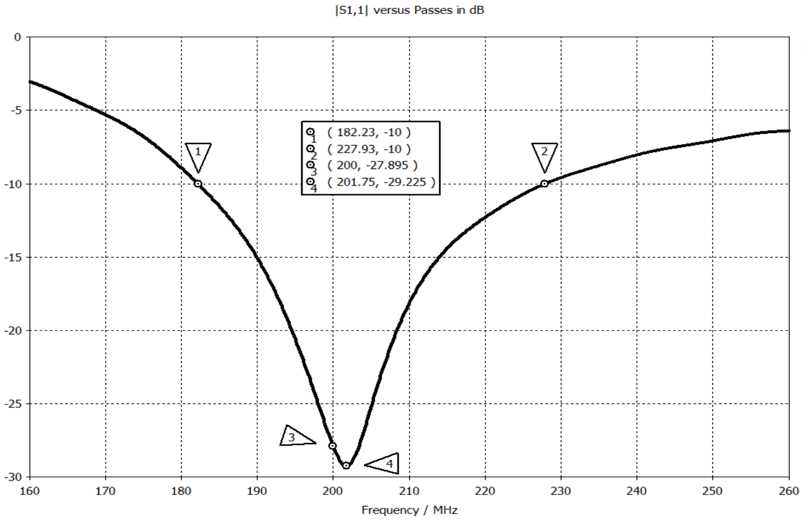


Fig. 11. Return loss of antenna with balun

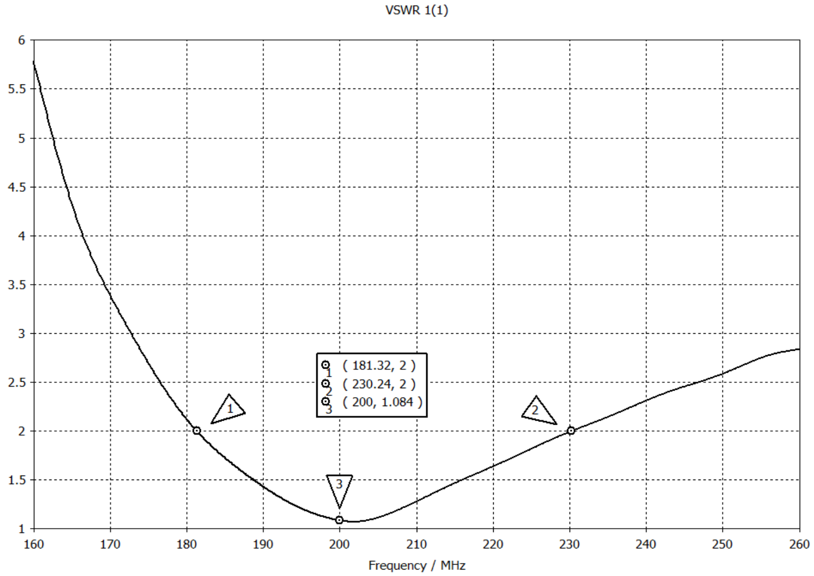


Fig. 12. VSWR of the antenna with balun

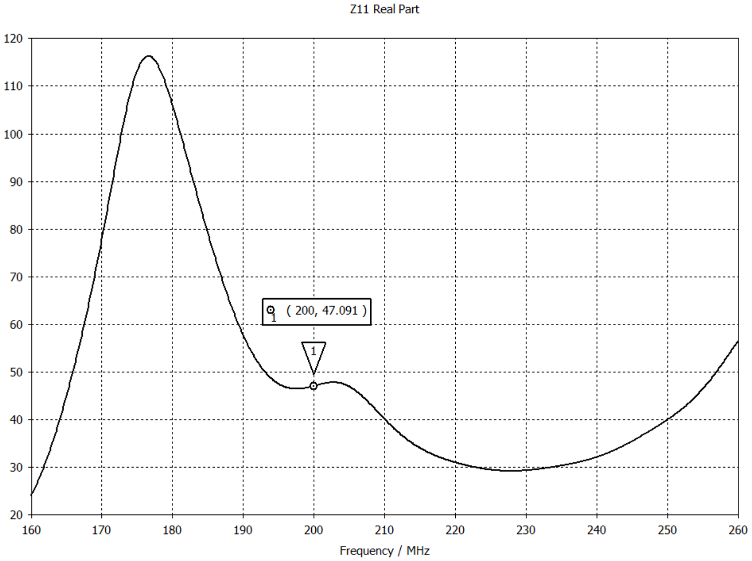
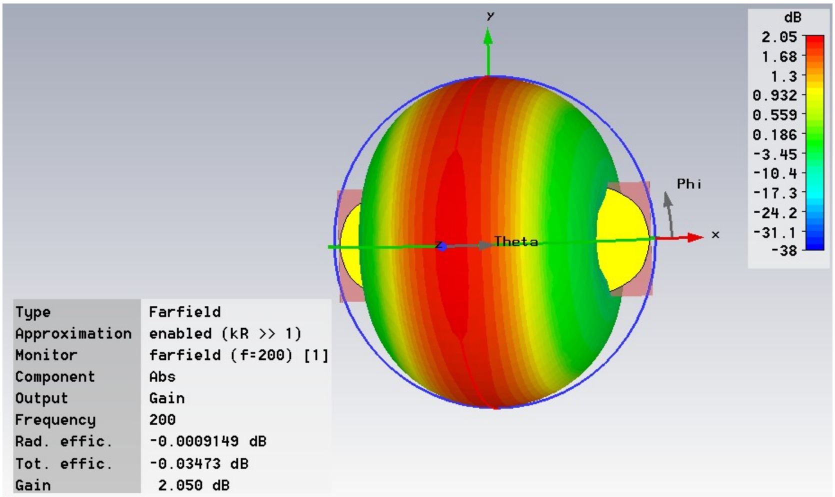


Fig. 13. The real part of impedance in case the antenna with balun

According to the above simulation results at the central frequency of 200 MHz, S11 is less than -25 dB and the real part of the impedance is 47 Ω. The bandwidth can be extended to 49 MHz, equivalent to 25% of the central frequency 200 MHz. The simulation results have shown that the matching impedance in this case is better than the case of the antenna without balun. So, the designed balun helps to increase the performance of antenna.



Type	Farfield
Approximation	enabled (kR >> 1)
Monitor	farfield (f=200) [1]
Component	Abs
Output	Gain
Frequency	200
Rad. effic.	-0.0009149 dB
Tot. effic.	-0.03473 dB
Gain	2.050 dB

Fig. 14. 3D radiation pattern of antenna at 200 MHz

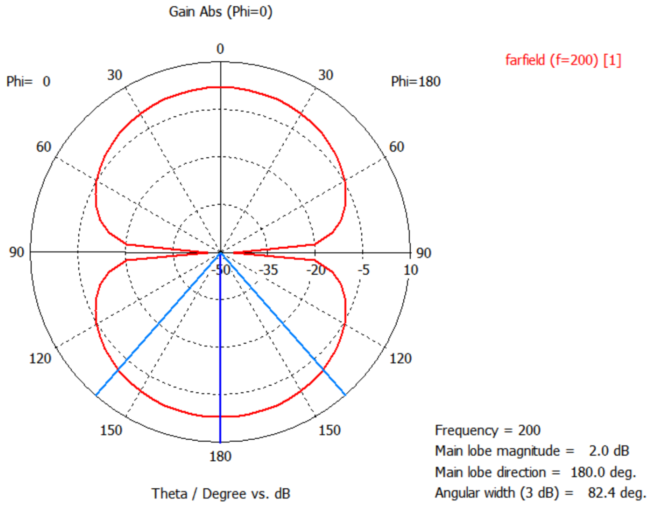


Fig. 15. Polar radiation pattern of antenna at 200 MHz

3D and Polar radiation patterns of the proposed antenna at 200 MHz are shown in Fig. 14 and 15, respectively. The antenna gain can be reached to 2 dB.

3 Experimental Results

Based on the design and simulation results, we have implemented the proposed antenna and balun in FR4 material. In this section, we will show the results of its implementation and measurements. The implemented antenna is shown in figure 16.

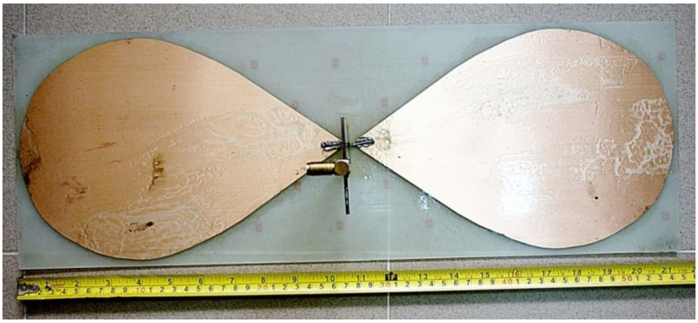
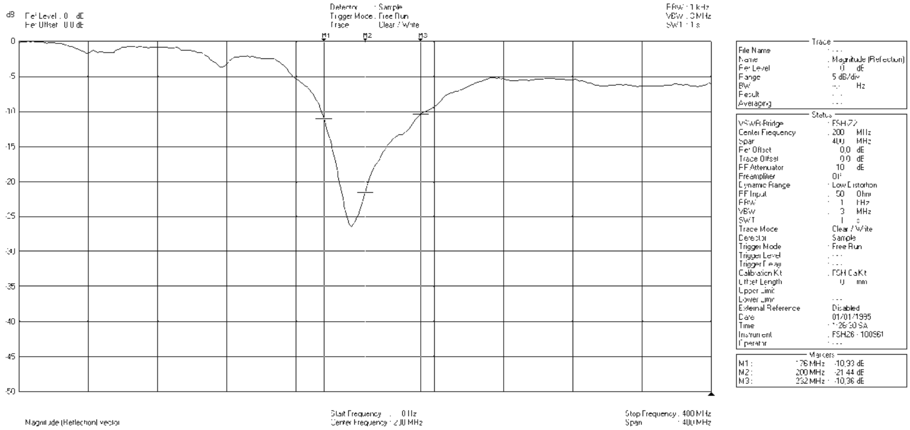


Fig. 16. Geometry of the implemented antenna

The measured reflection coefficient S11 and VSWR with wideband balun transformer line are shown in Fig. 17 and 18. It can be seen that our proposed antenna can work in the frequency band from 176 MHz to 232 MHz. The Smith Chart measurement of the proposed antenna is shown in Fig. 19. It has shown a good matching impedance. A comparison between simulation results and implementation results of S11 and VSWR values are shown in Tables 1 and 2. It can be seen that the performance of implementation is better than in simulation. This may be the difference from the characteristics of real FR4 material and parameters in simulation.

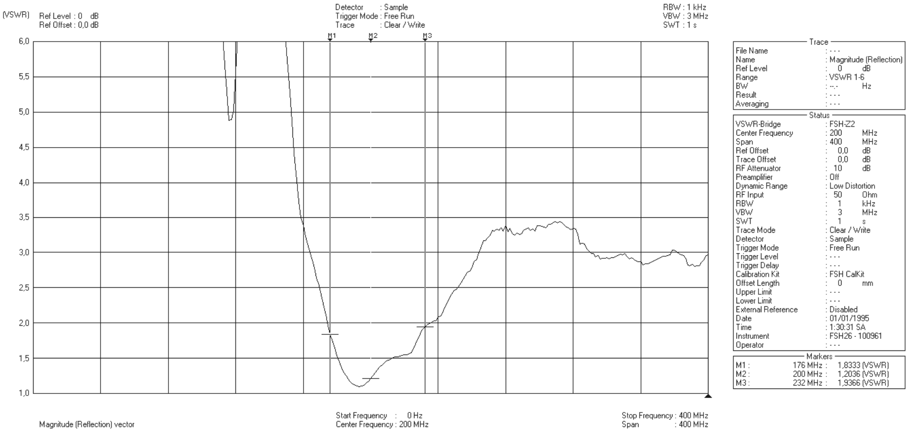


Trace
File Name : - - -
Name : Magnitude (Reflection)
Ref Level : 0 dB
Range : 5 dB/div
BW : --.- Hz
Result : - - -
Averaging : - - -

Status
VSWR-Bridge : FSH-Z2
Center Frequency : 200 MHz
Span : 400 MHz
Ref Offset : 0,0 dB
Trace Offset : 0,0 dB
RF Attenuator : 10 dB
Preamplifier : Off
Dynamic Range : Low Distortion
RF Input : 50 Ohm
RBW : 1 kHz
VBW : 3 MHz
SWT : 1 s
Trace Mode : Clear / Write
Detector : Sample
Trigger Mode : Free Run
Trigger Level : - - -
Trigger Delay : - - -
Calibration Kit : FSH CalKit
Offset Length : 0 mm
Upper Limit :
Lower Limit : - - -
External Reference : Disabled
Date : 01/01/1995
Time : 1:26:30 SA
Instrument : FSH26 - 100961
Operator : - - -

Markers
M1 : 176 MHz : -10,93 dB
M2 : 200 MHz : -21,44 dB
M3 : 232 MHz : -10,36 dB

Fig. 17. Measured reflection coefficient S11

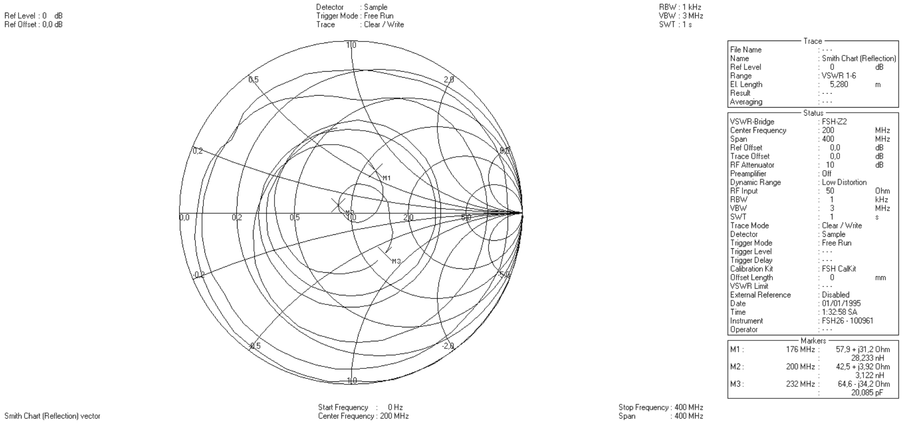


Trace
File Name : - - -
Name : Magnitude (Reflection)
Ref Level : 0 dB
Range : VSWR 1-6
BW : --.- Hz
Result : - - -
Averaging : - - -

Status
VSWR-Bridge : FSH-Z2
Center Frequency : 200 MHz
Span : 400 MHz
Ref Offset : 0,0 dB
Trace Offset : 0,0 dB
RF Attenuator : 10 dB
Preamplifier : Off
Dynamic Range : Low Distortion
RF Input : 50 Ohm
RBW : 1 kHz
VBW : 3 MHz
SWT : 1 s
Trace Mode : Clear / Write
Detector : Sample
Trigger Mode : Free Run
Trigger Level : - - -
Trigger Delay : - - -
Calibration Kit : FSH CalKit
Offset Length : 0 mm
Upper Limit : - - -
Lower Limit : - - -
External Reference : Disabled
Date : 01/01/1995
Time : 1:30:31 SA
Instrument : FSH26 - 100961
Operator : - - -

Markers
M1 : 176 MHz : 1,8333 (VSWR)
M2 : 200 MHz : 1,2036 (VSWR)
M3 : 232 MHz : 1,9366 (VSWR)

Fig. 18. VSWR measurement



```
Ref Level : 0   dB
Ref Offset : 0,0 dB

Detector     : Sample
Trigger Mode : Free Run
Trace        : Clear / Write

RBW : 1 kHz
VBW : 3 MHz
SWT : 1 s

Trace
File Name          : - - -
Name               : Smith Chart (Reflection)
Ref Level          :    0         dB
Range              : VSWR 1-6
El. Length         :    5,280     m
Result             : - - -
Averaging          : - - -

Status
VSWR-Bridge        : FSH-Z2
Center Frequency   : 200          MHz
Span               : 400          MHz
Ref Offset         :    0,0       dB
Trace Offset       :    0,0       dB
RF Attenuator      :   10         dB
Preamplifier       : Off
Dynamic Range      : Low Distortion
RF Input           :   50         Ohm
RBW                :    1         kHz
VBW                :    3         MHz
SWT                :    1         s
Trace Mode         : Clear / Write
Detector           : Sample
Trigger Mode       : Free Run
Trigger Level      : - - -
Trigger Delay      : - - -
Calibration Kit    : FSH CalKit
Offset Length      :    0         mm
VSWR Limit         : - - -
External Reference : Disabled
Date               : 01/01/1995
Time               : 1:32:58 SA
Instrument         : FSH26 - 100961
Operator           : - - -

Markers
M1 :        176 MHz :   57,9 + j31,2 Ohm
                    :         28,233 nH
M2 :        200 MHz :   42,5 + j3,92 Ohm
                    :          3,122 nH
M3 :        232 MHz :   64,6 - j34,2 Ohm
                    :         20,085 pF

Smith Chart (Reflection) vector

Start Frequency  :    0 Hz
Center Frequency : 200 MHz

Stop Frequency : 400 MHz
Span           : 400 MHz
```

Fig. 19. Smith Chart measurement

Table 2. Comparison Results between Simulation and Measurement of S11

Frequency (MHz)	Simulated S11 (dB)	Frequency (MHz)	Measured S11 (dB)
182.23	-10	176	-10.93
200	-27.9	200	-21.44
227.93	-10	232	-10.36

Table 3. Comparison Results between Simulation and Measurement of VSWR

Frequency (MHz)	Simulated VSWR	Frequency (MHz)	Measured VSWR
181.32	2	176	1.833
200	1.084	200	1.204
230.24	2	232	1.972

4 Conclusions

In the paper, a proposed novel wideband VHF antenna has been presented. We have designed, simulated, and implemented the antenna and a wideband balun. The measured results have shown that the proposed antenna has a wide frequency band from 176 MHz to 232 MHz, equivalent to 28% of the central frequency 200 MHz.

The wideband balun has also been designed to make a good matching impedance of the antenna. The patch antenna is designed based on the Lemniscate curve. The implementation of the antenna is extremely low cost, small size, and high gain. This proposed antenna is very suitable for wideband systems such as impulse GPR.

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