Improved Ultra-wide Bandwidth Bow-tie Antenna with Metamaterial Lens for GPR Applications

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***Abstract*—A new resistively loaded bow-tie antenna which can operate from 300 MHz to more than 3 GHz bandwidth is proposed. The proposed antenna employs a metamaterial lens to improve the forward gain and front-to-back ratio. The antenna radiates pulses with minimal late-time ringing and high peak amplitude. A stable radiation pattern obtained from 300 MHz to 2 GHz, makes it suitable for time domain as well as stepped frequency continuous wave (SFCW) GPR applications. The antenna is characterized by measurements of return loss, transmission scattering parameter, radiation pattern, gain, front-to-back ratio, and GPR B-scan with object buried under soil. The measured results are in good agreement with the simulation results.**

***Index Terms*—Bow-tie antenna, GPR, Metamaterial lens, Resistive loading**

I. Introduction

The common requirements for a GPR antenna are:

1) Ultra-wide bandwidth for high range resolution.
2) Low frequency operation for more depth of penetration.
3) High front-to-back ratio to minimize the clutter.
4) Good gain and radiation efficiency to increase the received power.

Resistively loaded bow-tie antenna is suitable for GPR applications because of its ultra-wide bandwidth and its ability to radiate short pulses. Lestari *et.al.* [1], [2] have done a lot of research on pulse radiating, resistively loaded, printed bow-tie antennas. In [1], bow-tie antenna with lumped resistors loading was proposed. The antenna operating bandwidth was from 0.42 to 1.67 GHz. In [2] capacitive slots were cut on the arms of the bow-tie and microwave absorbers were put on each arm, which serves as a resistive loading. Putting absorbers on the back side of the antenna also helped in back-lobe suppression. The impedance bandwidth (VSWR 2:1) has been from 0.5 to 5.1 GHz. Radiated pulse amplitude had become 154% compared to normal bow-tie antenna. A stable radiation pattern had been obtained up to 3 GHz. The input impedance of the antenna had been 100 Ω. The antenna size was 50 cm. Uduwawala *et.al.* [3] have done a detailed study of another type of bow tie antenna which is resistor loaded at the ends to suppress the end reflections. B. Wu et.al. [4] have designed a cavity backed, half ellipse shaped antenna with lumped resistor loading at the end. J. Wang et.al. has described the design of bow tie antennas with high radiation efficiency [5]. Vee dipole antennas [6] [7] were also explored for GPR applications. Logarithmic spiral antenna [8] is another choice of antenna at this frequency band.

Recently metamaterials are employed to improve various antenna parameters like bandwidth, directivity, etc. Researchers have applied metamaterials to improve the directivity of Vivaldi antenna [9]. Recently researchers were able to control the radiation pattern over a large bandwidth [10]. They were also used with planar folded dipole antennas [11]. Zhu *et.al.* [12] used metamaterial to improve the antenna gain as well as to convert polarization from linear to circular. However low frequency metamaterial and its application in antennas are scarce in the literature. Erentok *et.al.* [13], [14] have done a lot of work in sub-GHz frequency metamaterials and metamaterial inspired antennas.

In this paper, we describe a resistive loaded bow-tie antenna and its improvement in performance characteristics with the application of a planar metamaterial lens.The experimental results including GPR scan result is described in the paper.

II. Antenna Design

The proposed antenna is designed in four stages:

1) Resistively loaded bow-tie antenna design
2) Balun design for feeding the antenna with a 50 Ω microstrip port
3) Metamaterial lens design
4) Integrating metamaterial lens with the antenna.

A. Design of Bow-tie Antenna

The bow-tie antenna is designed on FR4 substrate with relative permittivity 4.4 and thickness 1.5 mm. Fig.1a shows the designed antenna in CST Microwave Studio. Fig.1b gives a close look at one arm of the bow tie at the feed location. A sheet of graphite of 1 mm thickness is put over each arm to obtain resistive loading as shown in Fig.7. Graphite, having a conductivity about $\left(\frac{1}{600}\right)^{th}$ of copper acts as a resistive load. Various design parameters with reference to Fig.1b are:

$Ls_0 = 10$ mm
$Ls_1 = 4.8$ mm, $Ls_2 = 4.7$ mm, $Ls_2 = 4.6$ mm, ...
$G_0 = 0.2$ mm, $G_1 = 0.3$ mm, $G_2 = 0.4$ mm, ...

The slot width increases as we move away from the feed point and hence the effective resistive loading increases towards the end. The overall size of the antenna is $30{\times}23$ cm^2.

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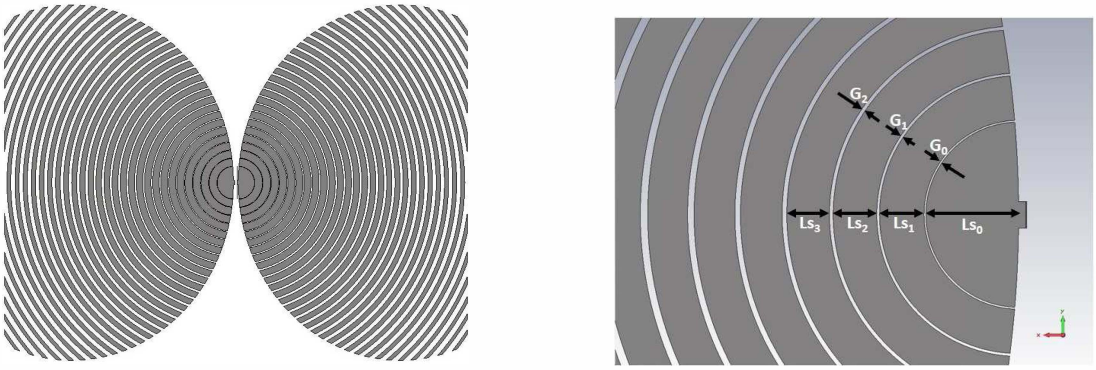


(a) Antenna model in CST Microwave Studio

(b) A closer view of one arm of the bow-tie at the feed point

Fig. 1. Bow-tie antenna model in CST Microwave Studio.

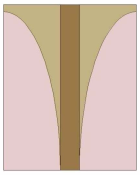


Fig. 2. Microstrip to parallel stripline transition.

B. Design of Ultra-Wideband Microstrip line to Parallel Stripline Transition

The basic bow-tie structure is followed from [2]. In almost all the bow-tie antenna designs [2], [1], the input impedance is optimised for 100 Ω because they used a linear flaring at the feed point. Here we propose to curve the feed point and got a 50 Ω impedance matching. The radius of curvature at the feed location is 100 mm. A 50 Ω microstrip line to parallel stripline transition [15] can be easily designed separately on a 50×20 mm^2 FR4 board with thickness 1.5 mm as shown in Fig.2. This connects vertically to the antenna as shown in Fig.7. The measured S parameters for the transition is shown in Fig.3. The measured insertion loss varies from 0.2 to 1.3 dB in the frequency range 0.3—3 GHz.

C. Design of Metamaterial Lens

We used the metamaterial unit cell structure proposed by Erentok *et.al.* [13] . They developed a volumetric negative index metamaterial with lumped inductor and capacitor loading and obtained 10% bandwidth at a center frequency of 400 MHz. Fig.4 shows the epsilon negative structure proposed in [13]. The unit cell was simulated using CST Microwave Studio. Fig.5 shows the S parameter values obtained for the unit cell simulation. Fig.6 shows the refractive index of the metamaterial, extracted using the simulated S parameter values [16]. It shows a negative refractive index at the frequencies 1.5 to 3 GHz. Below 1.5 GHz we get a positive refractive index. So we expect that, by employing this metamaterial lens to the antenna, we would get enhanced gain from 0.3—3 GHz. Also we expect the radiation pattern beamwidth to be broader than

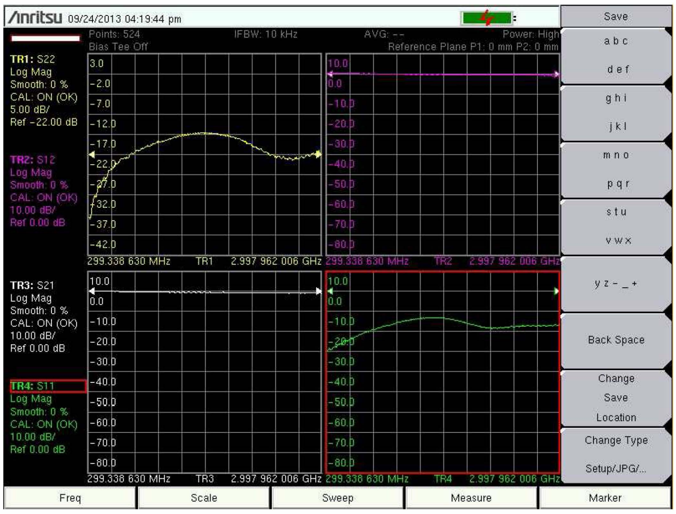


Fig. 3. Magnitude of S parameters vs frequency.

TABLE I
DESIGN VALUES IN MM

a	2	e	0.2774	h	1	k	0.5
b	3	f	0.2	i	10	l	1.1938
c	1	g	1	j	1	m	0.2
d	0.6096						

the conventional bow-tie below 1.5 GHz and narrower at the frequencies above 1.5 GHz. The various design parameters are given in Table I. The metamaterial lens is fabricated on FR4 substrate with relative permittivity 4.4 and thckness 1.5 mm.

D. Bow-tie Antenna with Metamaterial Lens

Now the metamaterial lens is placed in front of the bow-tie anetnna as shown in Fig.7. The distance between the antenna and the lens is optimized using CST Microwave Studio. The separation in the final design is 30 mm. The presence of metamaterial does not affect the input impedance of the antenna. The lens enhances the forward gain and hence front

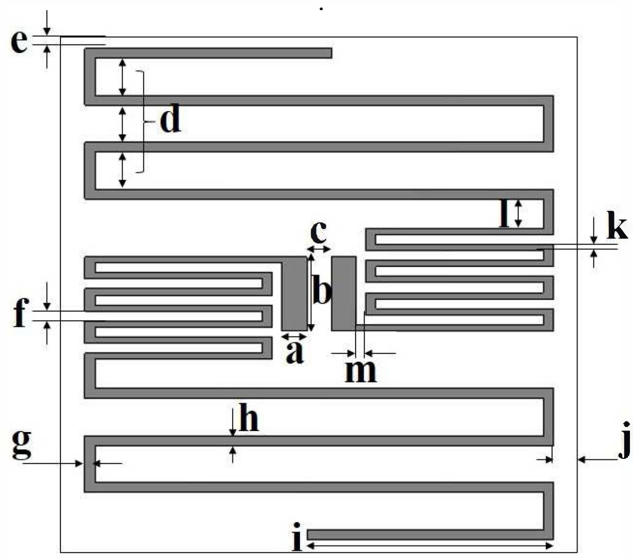


Fig. 4. Metamaterial unit cell [13]

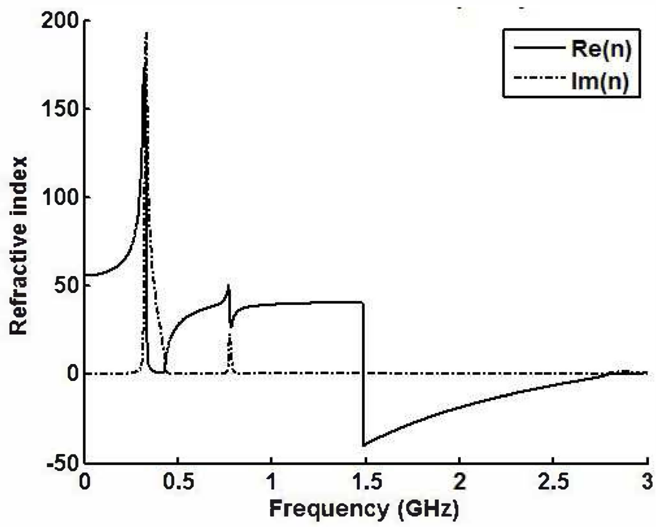


Fig. 6. Refractive index vs frequency.

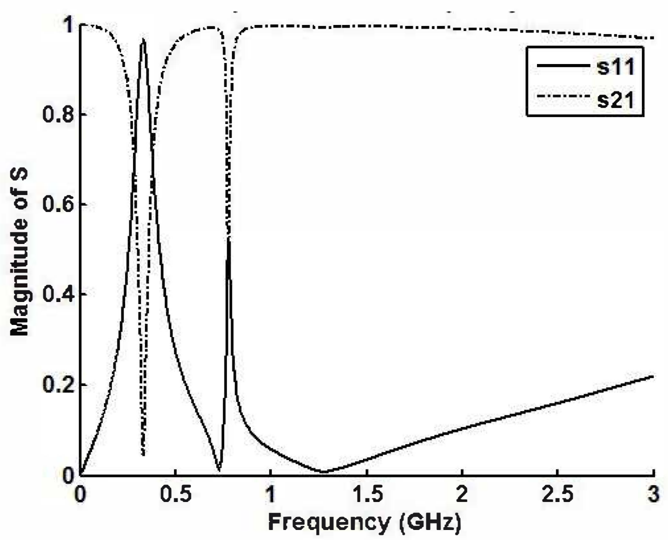


Fig. 5. Magnitude of S parameters vs frequency.

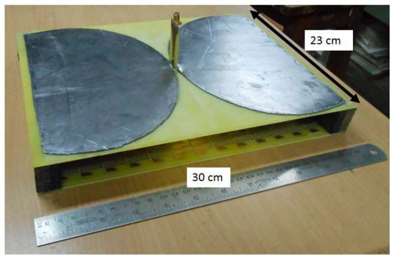


Fig. 7. Photograph of the fabricated antenna.

to back ratio is improved. The photograph of the fabricated antenna is shown in Fig.7. The results are discussed in next section.

III. Results and Discussions

Fig.8—11 gives the experimental results for the bow-tie antenna with metamaterial lens. The plot given in Fig.8 shows a return loss of at least 10 dB in the frequency range from 300 MHz to 3 GHz.

Fig.9 compares the measured gain with simulated gain of the antenna. The measured peak gain is 11.52 dB at 1.124 GHz. From simulation peak gain obtained is 8.3 dB at 1.2 GHz

Fig.10 compares the measured and simulated values of front to back ratio. The maximum value of measured front to back ratio is 15.39 dB at 1.46 GHz. In simulation maximum value is 15.46 dB at 1.8 GHz

Fig.11 shows the radiation pattern of the antenna at various frequencies indicated. It shows stable radiation pattern upto 2.02 GHz after which it deteriorates.

Fig.12 compares the measured boresight gain of the resistive loaded bow-tie antenna alone with that of bow-tie antenna with metamaterial lens attached. The maximum gain obtained without lens is 6.45 dB at 914 MHz. The figure shows a clear improvement in gain at all frequencies and gain is improved by at least 5 dB at frequencies above 1.2 GHz.

Fig.13 shows the measured front-to-back ratio of the bow-tie antenna with and without metamaterial lens. We can see a clear improvement of upto 16 dB in front to back ratio.

Fig.14 shows the measured S_{21} in time domain. $S_{21}(0)$ indicates the transmission in boresight direction and $S_{21}(180)$ indicates the transmission towards back side. The peak amplitude is 0.2073 mV in first case or 176.6% higher compared to 0.1173 mV in the second case.

An experimental GPR has been setup with the fabricated bow-tie antenna with metamaterial lens and is used to detect targets buried under test bed filled with sand. Fig.15 shows the measured GPR B-scan image of a metallic hollow rectangular

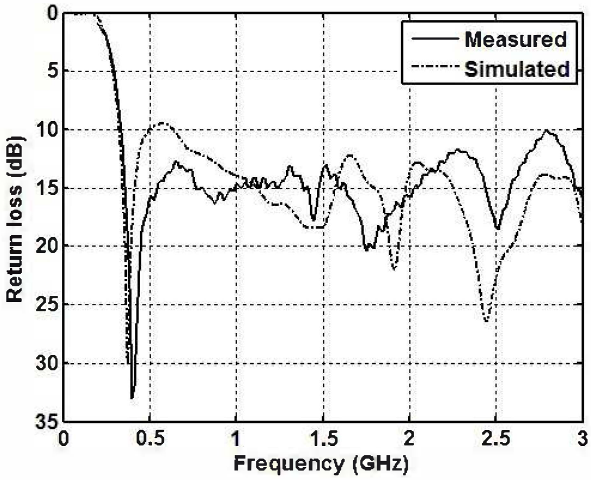


Fig. 8. Return loss vs frequency.

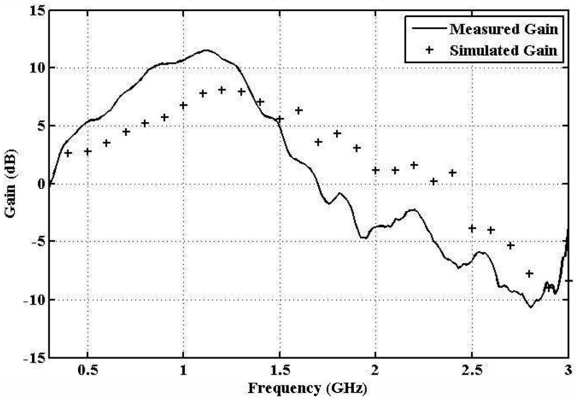


Fig. 9. Realized gain in the boresight direction vs frequency.

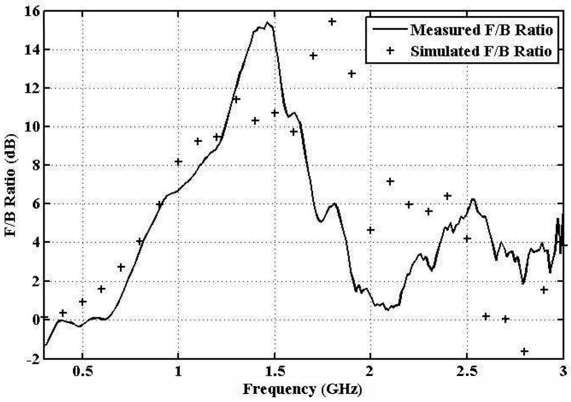


Fig. 10. Front-to-back ratio vs frequency.

object of size 42×20×11 cm^3 shown in the inset.

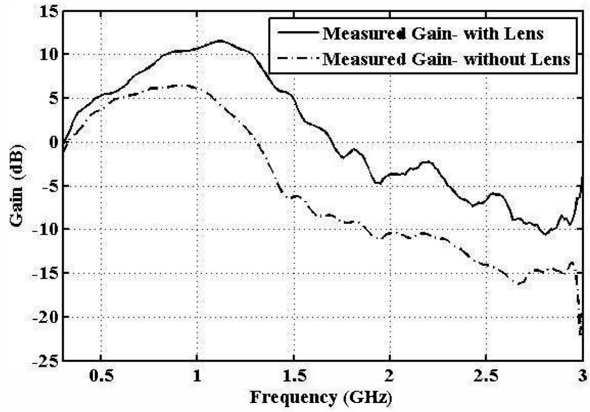


Fig. 12. Realized gain of bow-tie antenna with and without metamaterial lens.

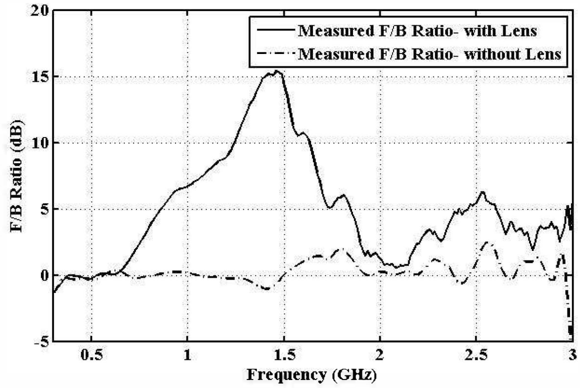


Fig. 13. Measured front-to-back ratio of bow-tie antenna with and without metamaterial lens.

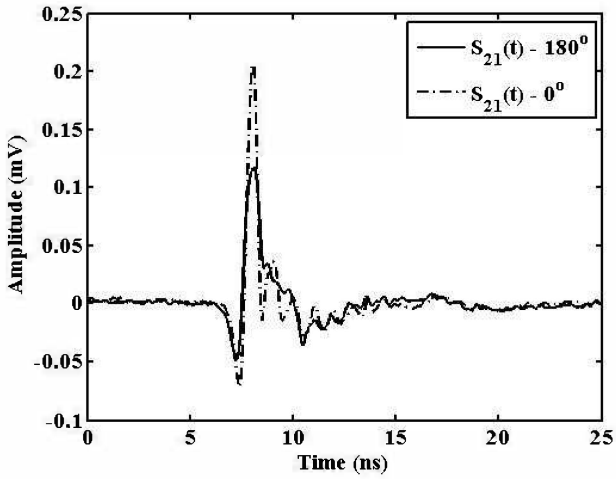
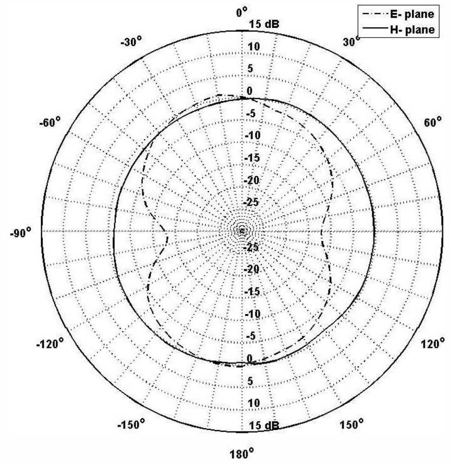


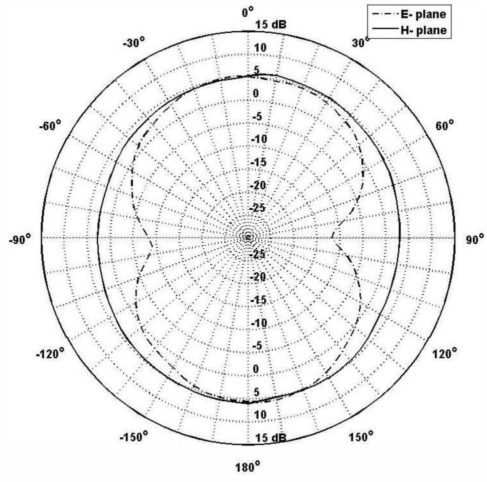
Fig. 14. $S_{21}(t)$ when two antenna see face to face and face to back.

IV. Conclusion

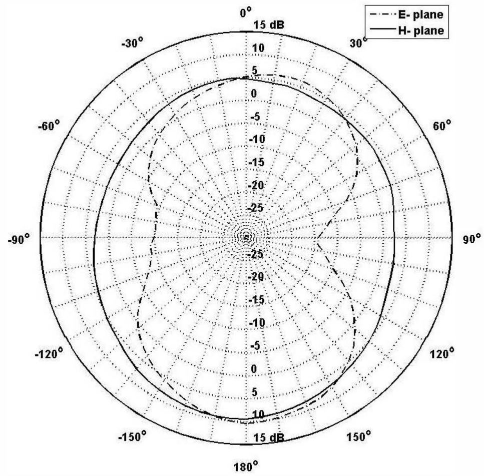
An improved design of resistively loaded bow-tie antenna is presented. With the use of a metamaterial lens, significant



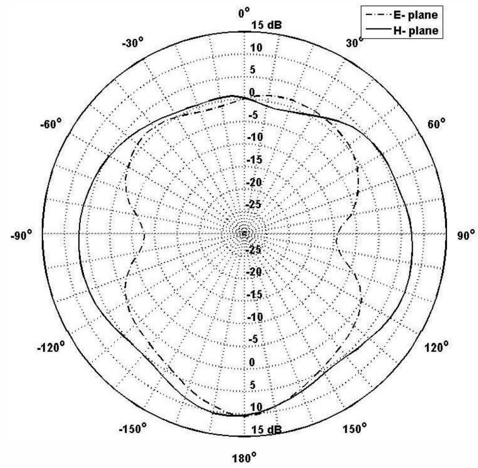
(a) 312 MHz



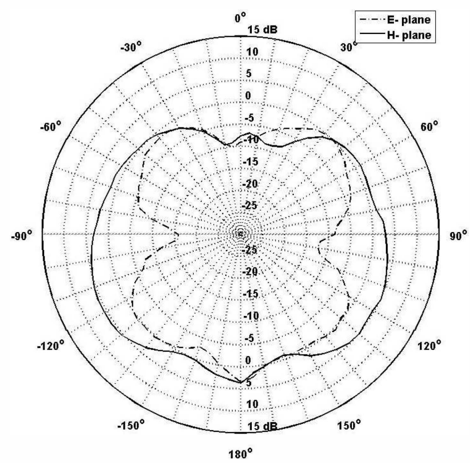
(b) 550 MHz



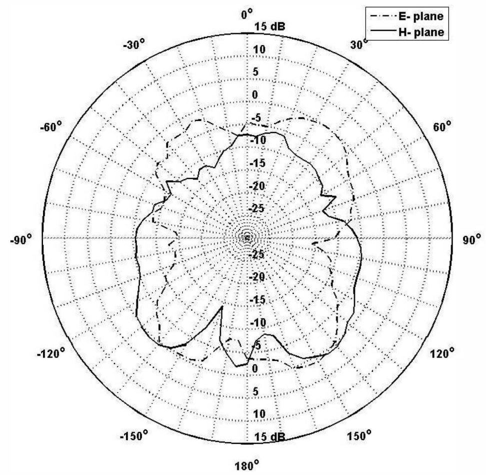
(c) 900 MHz



(d) 1.2 GHz



(e) 1.53 GHz



(f) 2.02 GHz

Fig. 11. Measured radiation pattern in two principal planes.

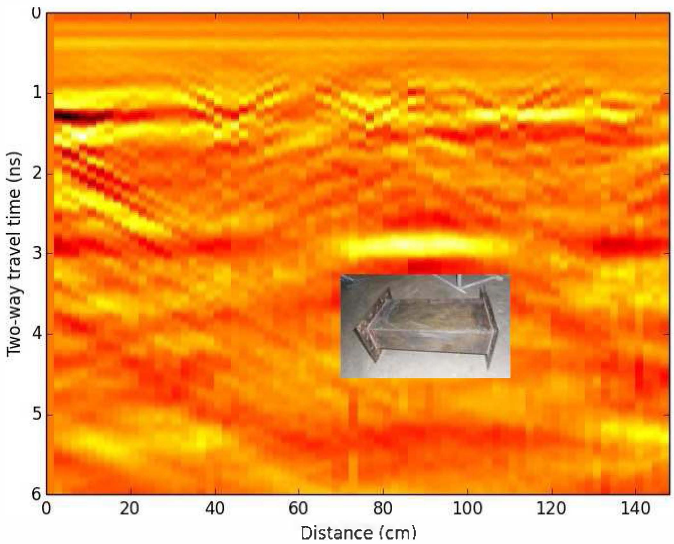


Fig. 15. B-scan image of a target buried in sand.

improvement in gain and front to back ratio is achieved. The designed antenna is also very compact in size, considering its lowest frequency of operation and ultra-wide bandwidth. Experimental results and comparison with simulation results are presented. Also a comparison with the bow-tie antenna without using the lens, is also presented. The fabricated antenna was used for GPR experiment and B-scan image of a buried object is also presented. The metamaterial lens promises a new way to improve the performance characteristics of GPR antennas, but the design of co-planar metamaterials at sub-GHz frequencies still requires lot of research.

References

[1] A. A. Lestari, E. Bharata, A. B. Suksmono, A. Kurniawan, A. G. Yarovoy, and L. P. Ligthart, "A modified bow-tie antenna for improved pulse radiation," *IEEE Transactions on Antennas and Propagation*, vol. 58, no. 7, pp. 2184–2192, 2010.

[2] A. A. Lestari, A. G. Yarovoy, and L. P. Ligthart, "RC-Loaded bow-tie antenna for improved pulse radiation," *IEEE Transactions on Antennas and Propagation*, vol. 52, no. 10, pp. 2555–2563, 2004.

[3] D. Uduwawala, M. Norgren, P. Fuks, and A. W. Gunawardena, "A deep parametric study of resistor-loaded bow-tie antennas for ground-penetrating radar applications using FDTD," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 42, no. 4, pp. 732–742, 2004.

[4] B. Wu, Y. Ji, and G. Fang, "Analysis of GPR UWB half-ellipse antennas with different heights of backed cavity above ground," *IEEE Antennas and Wireless Propagation Letters*, vol. 9, pp. 130–133, 2010.

[5] J. Wang, Y. Su, C. Huang, M. Lu, and Y. Li, "Design of bow-tie antenna with high radiating efficiency for impulse GPR," in *IEEE International Geoscience and Remote Sensing Symposium (IGARSS), 2012*, 2012, pp. 594–597.

[6] K. Kim and W. R. Scott, "Design of a resistively loaded Vee dipole for ultrawide-band ground-penetrating radar applications," *IEEE Transactions on Antennas and Propagation*, vol. 53, no. 8, pp. 2525–2532, 2005.

[7] H. Yang and K. Kim, "Ultra-wideband impedance matching technique for resistively loaded Vee dipole antenna," *IEEE Transactions on Antennas and Propagation*, vol. 61, no. 11, pp. 5788–5792, Nov. 2013.

[8] B. J. Thaysen and K. B. Jakobsen, "A logarithmic spiral antenna for 0.4 to 3.8 GHz," *Applied Microwave and Wireless*, vol. 13, no. February, pp. 32–45, 2001.

[9] B. Zhou and T. J. Cui, "Directivity enhancement to Vivaldi antennas using compactly anisotropic zero-index metamaterials," *IEEE Antennas and Wireless Propagation Letters*, vol. 10, pp. 326–329, 2011.

[10] M. Q. Qi, W. X. Tang, H.-X. Xu, H. F. Ma, and T. J. Cui, "Tailoring radiation patterns in broadband with controllable aperture field using metamaterials," *IEEE Transactions on Antennas and Propagation*, vol. 61, no. 11, pp. 5792–5798, Nov. 2013.

[11] A. Vallecchi, J. R. D. Luis, F. Capolino, and F. D. Flaviis, "Low profile fully planar folded dipole antenna on a high impedance surface," *IEEE Transactions on Antennas and Propagation*, vol. 60, no. 1, pp. 51–62, 2012.

[12] H. L. Zhu, S. W. Cheung, K. L. Chung, and T. I. Yuk, "Linear-to-circular polarization conversion using metasurface," *IEEE Transactions on Antennas and Propagation*, vol. 61, no. 9, pp. 4615–4623, 2013.

[13] A. Erentok, R. W. Ziolkowski, J. a. Nielsen, R. B. Greegor, C. G. Parazzoli, M. H. Tanielian, S. a. Cummer, B.-I. Popa, T. Hand, D. C. Vier, and S. Schultz, "Lumped element-based, highly sub-wavelength, negative index metamaterials at UHF frequencies," *Journal of Applied Physics*, vol. 104, p. 034901, 2008.

[14] A. Erentok and R. W. Ziolkowski, "Metamaterial-inspired efficient electrically small antennas," *IEEE Transactions on Antennas and Propagation*, vol. 56, no. 3, pp. 691–707, 2008.

[15] S.-G. Kim and K. Chang, "Ultrawide-band transitions and new microwave components using double-sided parallel-strip lines," *IEEE Transactions on Microwave Theory and Techniques*, vol. 52, no. 9, pp. 2148–2152, 2004.

[16] D. R. Smith, D. C. Vier, T. Koschny, and C. M. Soukoulis, "Electromagnetic parameter retrieval from inhomogeneous metamaterials," *Physical Review E*, vol. 71, no. 3, p. 036617, Mar. 2005.