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PARTIAL DIELECTRIC LOADED TEM HORN AND REFLECTOR ANTENNA DESIGNS FOR ULTRAWIDE BAND GROUND PENETRATING RADAR SYSTEMS

A.S. TURK, A.K. KESKIN, M. ILARSLAN

This paper deals with ultra-wide band (UWB) TEM horn antenna designs and their usage as feeder of parabolic reflector, which are suitable for down-looking and forward-looking vehicle-mounted impulse GPR systems, respectively. On this scope, partial dielectric loaded, Vivaldi form and array configurations of the TEM horn structure are investigated, designed, simulated and measured. Vivaldi shaped TEM horn fed parabolic reflector antenna prototype is proposed to reach hyper-wide band impulse radiation performances from 300 MHz up to 15 GHz for multi-band GPR operation that can provide both deep and high resolution imaging. The gain and input reflection performances are demonstrated with measurement results.

Keywords: Ultra-wide band antenna, TEM horn, Parabolic reflector, Ground penetrating radar, Impulse radiation.

I. INTRODUCTION

Ultra wide band (UWB) antennas have been using increasingly in many applications of high-speed wireless communication, high resolution noise radar, RF jamming and EMC test systems. The operational frequency bands of the impulse and UWB radar systems can be very broad starting from VHF band up to millimeter waves. The UWB operation provides some critical advantages, such as improved detection, adaptive ranging and target resolution performances. There are a few types of UWB antennas which operate at various frequency bands, such as horn, spiral, bi-conical and log-periodic arrays [1].

In recent years, ground-penetrating radar (GPR) has become a leading non-destructive testing and through-wall imaging technology for the detection, identification, and imaging of subsurface structures and buried objects such as pipes, mines, gaps, water channels, tunnels, roads and concealed bodies [2]. The central frequency and bandwidth of the GPR signal are the key factors for the detection performance. The higher frequencies are needed for better resolution, nevertheless the lower frequency bands are preferred to detect something buried too deep due to the dramatically increased wave attenuation in the soil with increasing frequency. Thus, UWB GPR systems are proposed to benefit from both low and high frequencies. For impulse GPR, the impulse durations can vary from a few nanoseconds to hundred picoseconds corresponding to a broad spectrum from 100 MHz to 10 GHz. It can be extended up 15 GHz for stepped-frequency GPR systems, which use microwave tomography methods for high resolution imaging [3].

The target detection and identification performance of the GPR depends significantly on the proper design of the UWB transmitter and receiver (T/R) antennas, which should have high gain, narrow beam, low side lobe and input reflection levels over the wide operational frequency band [2]. On this scope, TEM horn and double-ridged horn antennas (DRHA) are one of most favorites due to their high gain, narrow beam and low input reflection characteristics over 20:1 bandwidth ratio [3]. The TEM horn antenna consists of a pair of triangular or circular slice shaped conductors forming some V-dipole [4]. The partial dielectric loading (PD) techniques can be applied to improve the UWB gain performances [5]. For instance, the PD-TEM horn was introduced by Turk as an efficient UWB impulse radiator over 20:1 frequency band [6-7]. Furthermore, its array combination was designed to obtain extended UWB characteristics up to 50:1 [8].

The DRHA operates at very wide frequency band by using ridges inside the horn that adjust the upper and lower cut-off frequencies of the propagating modes [9]. The antenna gain is sufficiently high and almost stable over the wide band. Dielectric aperture loading methods (i.e. hemispherical lenses) can be applied to improve the gain performance at high frequencies. Nevertheless, such big lenses increase the physical dimensions and weight of the antenna. Hence, the partial dielectric lens loading has also been proposed for DRHA to improve the gain performance and to eliminate radiation pattern deterioration without significant changes on the antenna sizes and weight [10].

This paper starts with a generic survey for UWB TEM horn antenna types, which are most suitable design models for multi-sensor adaptive, stepped-frequency and impulse mode UWB GPR systems. For example, the partial dielectric loaded TEM (PDTEM) horn, Vivaldi shaped TEM horn (PDVA) and array combinations have been introduced by Turk, as efficient UWB impulse radiators operating from 150 MHz up to 10 GHz [6-8]. A novel version of Vivaldi shaped TEM horn design is proposed as feeder of the parabolic reflector (PR) to obtain hyper-wide band antenna characteristics from 200 MHz up to 15 GHz. The partially loaded transmission line antenna method (PLTLM) and the analytical regularization method (ARM) are used for proper designs of TEM horn feeder and reflector antennas, respectively. The antenna models were designed and measured between 0.1–15 GHz. The antenna gain, VSWR and radiation pattern performances are presented and compared with standard 1-18 GHz DRHA. It is shown that PDTEM and PDTEM-PR designs are highly suitable for multi-band GPR operations, due to advantages of up to 10 dB enhanced gain performances over 1:100 bandwidth ratio.

II. PLTLM PROCEDURE FOR TEM HORN ANALYSIS

TEM horn is a kind of travelling wave antenna. Hence, its structure can be considered as combination of micro-strip transmission line segments, which are characterized by their local geometrical and constitutional structure parameters. The staircase modelling is used for the analysis. 3D antenna geometry is firstly divided into N number of elementary cells, which are chosen locally homogeneous and sufficiently small in wavelength. Then, the structure is reduced to the equivalent 1D transmission line with corresponding characteristic impedance definitions. The input impedance of each line segment and its characteristic impedance are expressed as [6]:

$$Z_{in}^{n} = Z_{0}^{n}\frac{Z_{in}^{n+1} + jZ_{0}^{n}\tan\beta_{n}l_{n}}{Z_{0}^{n} + jZ_{in}^{n+1}\tan\beta_{n}l_{n}}\ ;\ n=1,2,...,N \qquad (1)$$

$$Z_{0}^{n} = 138\sqrt{\frac{\mu_{r}^{n}}{\varepsilon_{r}^{n}}}\log\frac{8}{\left(w_{n}/d_{n}\right)}\ ;\ \text{for}\ \left(w_{n}/d_{n}\right)\le 1 \qquad (2)$$

where, β_n is propagation constant, l_n is segment length, w_n is segment width, d_n is segment height, L is the total arm length, $\beta_n = \frac{2\pi f}{c}\sqrt{\mu_r^n\varepsilon_r^n}$ and Z_{in}^{N+1} is the equivalent antenna line output impedance. The input and local reflection coefficients of the n*th* segment line are given by Eqs. (3) and (4):

$$\Gamma_{in}^{n} = \frac{Z_{in}^{n} - Z_{0}^{n-1}}{Z_{in}^{n} + Z_{0}^{n-1}}\ ;\ n = 1,2,...,N \qquad (3)$$

$$\Gamma^{n}(z) = \Gamma_{in}^{n+1}e^{-j2\beta_{n}(l_{n+1}-z)}\ ;\ z\in l_{n};0\le z\le L \qquad (4)$$

Using the Eq. (4), the discrete voltage and current distribution functions over the antenna line are determined as follows:

$$\left.\begin{aligned} V^{n}(z) &= V_{0+}^{n}e^{-j\beta_{n}z}\left[1+\Gamma^{n}(z)\right] \\ I^{n}(z) &= I_{0+}^{n}e^{-j\beta_{n}z}\left[1-\Gamma^{n}(z)\right] \end{aligned}\right\}\ ;\ z\in l_{n};n=1,2,...,N \qquad (5)$$

V_{0+}^{n} and I_{0+}^{n} coefficients are calculated iteratively using the initial values, such as the excitation voltage at the antenna line feed and the source impedance. The integral equation techniques are used to compute radiated field. This method is faster than direct numerical techniques [7].

III. PARTIAL DIELECTRIC LOADED TEM HORN ANTENNA DESIGNS

TEM horn structure consists of a pair of triangular or circular slice shaped conductors forming some V-dipole structure and characterized by *L, d,* α and θ parameters which correspond to the arm length of antenna, feed point gap, conductor plate angle and elevation angle, respectively [4]. The conventional TEM horn shows band pass filter-like gain behavior due to the arm length that limits the lower cut-off frequency of the radiated pulse. Thus, dielectric filling and partial dielectric loading techniques are employed to broaden the operational band up to twice [5-6].

Some TEM horn, PDTEM horn, PDVA and PDTEM horn array design configurations are given in Table 1 and Fig. 1, with the gain and VSWR measurement results shown in Fig. 2. It is seen that partial dielectric loading approach used in PDVA-10 can attain two times broadened gain characteristics than VA-10 with a VSWR level less than 2. The grating arm model PDVA structure in Fig. 1c, which is basically Vivaldi shaped wing version of the PDTEM horn is a special design proposal for metal detector adaptive operation of GPR [7].

Table 1

UWB GPR antenna designs

Fig	Model	**Physical Descriptions**
1a	TEM-10	$\alpha = 20°$, $\theta = 60°$, $d = 0.15$ cm, $L = 10$ cm, $\varepsilon_r = 1$, air-filled
	PDTEM-10	$\alpha = 20°$, $\theta = 60°$, $d = 0.15$ cm, $L = 10$ cm, $\varepsilon_r = 3$, dielectric loaded
1b	VA-10	$\alpha = 20°$, $\theta \in (0°–160°)$, $d = 0.4$ cm, $L = 10$ cm, $\varepsilon_r = 1$, air-filled
	PDVA-10	$\alpha = 20°$, $\theta \in (0°–160°)$, $d = 0.4$ cm, $L = 10$ cm, $\varepsilon_r = 3$, dielectric-loaded
1c	PDTE-MA-45	$\alpha_1 = 20°$, $\theta_1 = 90°$, $d_1 = 0.25$ cm, $L_1 = 45$ cm, *aperture*: 10 cm × 15 cm; $\alpha_2 = 20°$, $\theta_2 = f(l) \in (0°–120°)$, $d_2 = 0.2$ cm, $L_2 = 25$ cm, Dielectric profile: $\varepsilon_r = 3.5$, $a_1 = 4$ cm, $a_2 = 13$ cm, $b_1 = 3$ cm, $b_2 = 9$ cm, $b_3 = 7$ cm, $t = 5.5$ cm
2	PDVA-30	$\alpha = 20°$, $\theta \in (0°–160°)$, $d = 0.5$ cm, $L = 30$ cm, $\varepsilon_r = 2.1$, dielectric-loaded

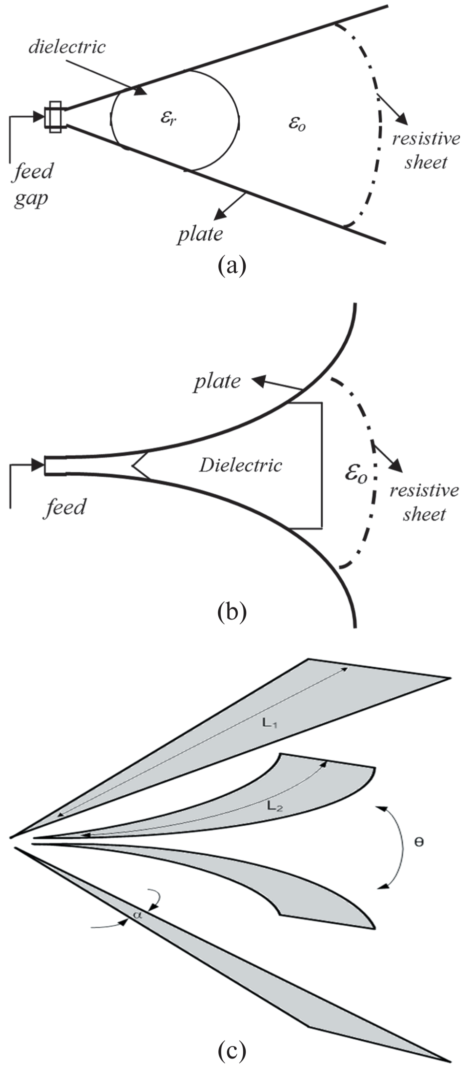

Fig. 1. TEM horn design illustrations: (a) PDTEM horn geometry (side view); (b) Vivaldi form TEM horn (side view); (c) PDTEM horn array (3D view, adapted from [8])

For vehicle mounted systems, the array combination of PDVA with TEM horn antenna can be proposed (see Fig. 1c) for hyper-wide band GPR operations to extend bandwidth ratios up to 50:1 (150 MHz to 10 GHz) [8]. Moreover, partial dielectric loading method can also yield about 5 dB gain increment for standard double-ridged horn antenna structures [10].

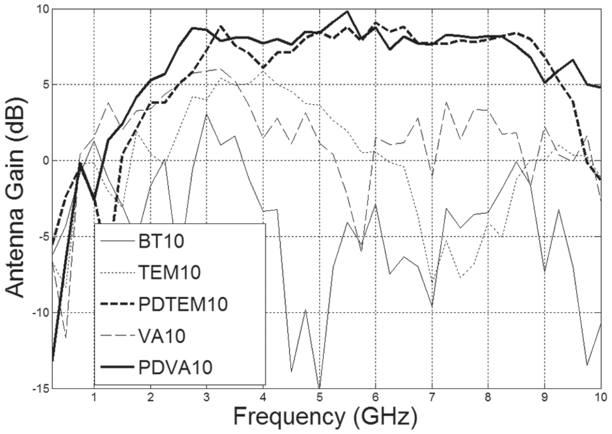

Fig. 2. Antenna gain characteristics of TEM horn designs

The geometrical view of the Vivaldi shaped TEM horn designed as an UWB feeder for parabolic reflector is shown in Fig. 3. The near field illumination of this antenna is calculated by PLTLM (see Section II) and then, the ARM procedure described in Section IV is used for computation of the UWB reflector radiation.

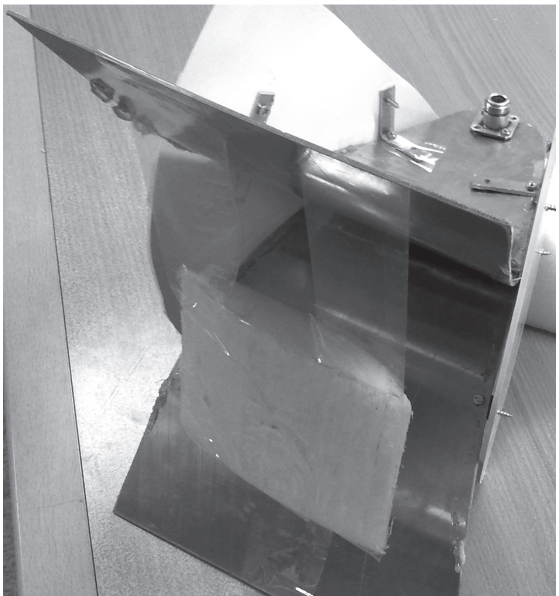

Fig. 3. Designed PDTEM horn feeder for parabolic reflector

IV. ARM FORMULATION FOR PARABOLIC REFLECTOR

Scalar diffraction problem of an infinitely long, smooth, longitudinally homogeneous and perfectly conducting cylindrical obstacle corresponds to the Dirichlet boundary condition for E-polarized incident wave. Considering that XOY plane cross section is denoted by the closed contour S, the incident and scattered scalar wave functions ($u^i(p)$ and $u^s(p)$) must satisfy the Helmholtz equation given in Eq. (6) and the Dirichlet boundary condition in Eq. (7) [11].

$$\left(\Delta + k^2\right)u^s(p) = 0, \quad p \in R^2 \backslash S \tag{6}$$

$$u^{s(+)}(p) = u^{s(-)}(p) = -u^i(p), \quad p \in S \tag{7}$$

where, S smooth contour of the domain D in 2D space R^2 that belongs to the smoothness class $C2,\alpha$ [11]. $u^{s(+)}(p)$ and $u^{s(-)}(p)$ are limiting values of $u^s(p)$ in the inner and the outer sides of S, respectively. The solution of the BVP is written in Eq. (8) using Green's formula and the boundary condition in Eq. (7).

$$-\frac{i}{4}\int_S \left[H_0^{(1)}(k|q-p|)Z(p)\right]dl_p = -u^i(q), \quad q,p \in S \tag{8}$$

where, $Z(p) = \dfrac{\partial u^{s(-)}(p)}{\partial n} - \dfrac{\partial u^{s(+)}(p)}{\partial n}$, $p \in S$; n is the unit outward with respect to S normal of the point p. The unknown function $Z(p)$ is constructed by solving Eq. (8), and using parameterization of the S contour specified by the function $\eta(\theta)=(x(\theta), y(\theta))$ that smoothly parameterizes the contour S by the points of $\theta \in [-\pi,\pi]$. The integral equation representation of the first kind in Eq. (8) can be equivalently rewritten by means of the $\eta(\theta)$ parameterization as follows:

$$\frac{1}{2\pi}\int_{-\pi}^{\pi}\left\{\ln\left|2\sin\frac{\theta-\tau}{2}\right| + K(\theta,\tau)\right\}Z_D(\tau)d\tau = g(\theta) \\ \theta \in \left[-\pi,\pi\right] \tag{9}$$

with the unknown function $Z_D(\tau)$ and the given function $g(\theta)$, where,

$$Z_D(\theta) = l(\theta)Z(\eta(\theta)),\ g(\theta) = -u^i(\eta(\theta)); \\ \theta \in \left[-\pi,\pi\right] \tag{10}$$

$$l(\theta) = \left([x'(\theta)]^2 + [y'(\theta)]^2\right)^{1/2} > 0, \\ x(\theta), y(\theta) \in C^\infty\left(Q^1\right) \tag{11}$$

Here $K(\theta,\tau)$ function is rather smooth section of the Green's function in comparison with $\ln|2\sin\frac{\theta-\tau}{2}|$ part that represents the main singularity of the Eq. (4). The functions in Eq. (9) are represented by their Fourier series expansions with ks,m, zm, gm coefficients. Subsequently, one can obtain an infinite system of the linear algebraic equations of the second kind [11]:

$$\hat{z}_s + \sum_{m=-\infty}^{\infty}\hat{k}_{s,m}\hat{z}_m = \hat{g}_s, \quad s = \pm 1, \pm 2,.. \tag{12}$$

where,

$$\hat{k}_{s,m} = -2\tau_s\tau_m\left[k_{s,-m} + \frac{1}{2}\delta_{s,0}\delta_{m,0}\right],$$

$$\hat{z}_n = \tau_n^{-1}z_n, \hat{g} = -2\tau_s g_s$$

$$\tau_n = \max(1,|n|^{1/2}), \quad n = 0, \pm 1, \pm 2,.. \tag{13}$$

and $\delta_{s,0}$ is the Kronecker delta function. Finally, the scattered field $u^s(q)$ for $q \in R^2$ are obtained by the integral equation representation of the Eq. (9) with any required accuracy by the truncation method [12].

The ARM procedure is derived for analysis of scattering from parabolic reflector antenna. The 2-D cylindrical reflector structure illustrated in Fig. 4 is considered. The cross-section of the reflector is a parabolic arc of the outer focus *b*, inner focus *a* and thickness *c*. It is modeled in ARM as a closed contour *L* goes from point *A* to point *D* and back to *A* which corresponds to $\theta\in[-\pi,\pi]$. The total contour *L* which consists of four parts is defined as:

$$L = L_{AB} + L_{BC} + L_{CD} + L_{DA}\text{; Total contour length} \quad (14)$$

$$L_{AB} = b\tan\left(\frac{\psi_{02}-\psi_{01}}{2}\right)\text{; Outer contour length} \quad (15)$$

$$L_{CD} = a\tan\left(\frac{\psi_{02}-\psi_{01}}{2}\right)\text{; Inner contour length} \quad (16)$$

$$\left.\begin{matrix} L_{BC} = R\pi c_1 \\ L_{DA} = R\pi c_2 \end{matrix}\right\}\text{; Edge contour lengths} \quad (17)$$

where

$$c_1 = \frac{b-a}{1+\cos\psi_{01}}\,,\ c_2 = \frac{b-a}{1+\cos\psi_{02}} \quad (18)$$

$\psi_{02} = -\psi_{01} = 44°$ and the edge-rolling coefficient *R* is 1.

The parameterization of the contour line is separately implemented from *A* to *D* and back to *A* by means of the variable $l\in[A,D]$ as follows [13]:

$$x = -\frac{2b\cos\phi_1}{1+\cos\phi_1} \quad y = \frac{2b\sin\phi_1}{1+\cos\phi_1}\text{; } l\in[A,B] \quad (19)$$

$$x = -\frac{2a\cos\phi_2}{1+\cos\phi_2} \quad y = \frac{2a\sin\phi_2}{1+\cos\phi_2}\text{; } l\in[C,D] \quad (20)$$

$$\left.\begin{aligned} x &= c_2\cos[(-l+L_{AB})/c_2+\pi-\psi_{02}]- \\ &-\frac{(a+b)\cos\psi_{02}}{1+\cos\psi_{02}}-(R-1)c_2\cos\psi_{02} \\ y &= c_2\sin[(-l+L_{AB})/c_2+\pi-\psi_{02}]+ \\ &+\frac{(a+b)\sin\psi_{02}}{1+\cos\psi_{02}}-(R-1)c_2\sin\psi_{02} \end{aligned}\right\}; \quad l\in(B,C) \quad (21)$$

$$\left.\begin{aligned} x &= c_1\cos[(-l+L_{CD})/c_1+\pi-\psi_{01}]- \\ &-\frac{(a+b)\cos\psi_{01}}{1+\cos\psi_{01}}-(R-1)c_1\cos\psi_{01} \\ y &= c_1\sin[(-l+L_{CD})/c_1+\pi-\psi_{01}]+ \\ &+\frac{(a+b)\sin\psi_{01}}{1+\cos\psi_{01}}-(R-1)c_1\sin\psi_{01} \end{aligned}\right\}; \quad l\in(D,A) \quad (22)$$

where

$$l=(\theta+\pi)L/(2\pi)\ ;\ \ l\in[0,L]\to(\theta,\tau)\in[-\pi,\pi] \quad (23)$$

$$\varphi_1 = \psi_{01} + [(\psi_{02}-\psi_{01})l/L_{AB}] \quad (24)$$

$$\varphi_2 = \psi_{02} - [(\psi_{02}-\psi_{01})(l-L_{BC})/(L_{CD}-L_{BC})] \quad (25)$$

The PDVA model TEM horn feeder is assumed to be located on the focus of the reflector. The near field illumination of the PDVA-30 on the reflector is defined as the incident wave at ARM algorithm.

V. UWB REFLECTOR DESIGN AND PERFORMANCES

The geometry of the designed reflector antenna with PDVA-30 feeder is given in Fig. 4, with the numerical ARM results shown in Fig. 5. This structure can also be adapted for offset feeding, which is more suitable in forward-looking GPR applications due to low tilt angle.

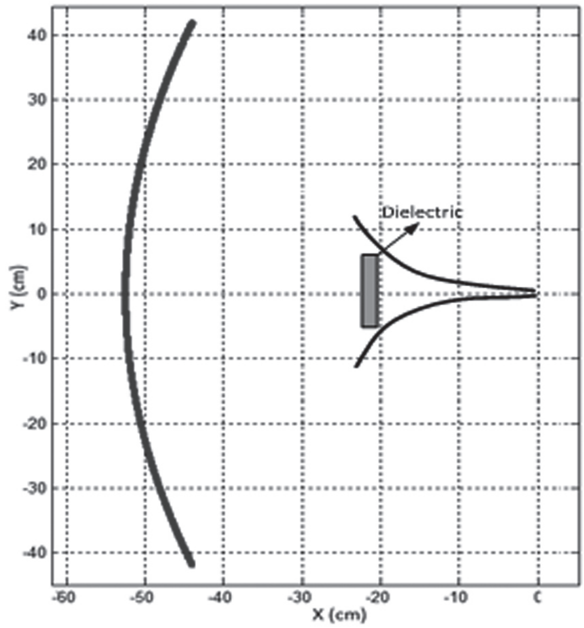

Fig.4. 2D cross-section geometry of parabolic reflector antenna with PDTEM horn feeder

The measurement results plotted in Figs. 6-7 show that radiated impulse signal has highly narrow beam widths and 10 dB improved gain performances can be achieved over 50:1 bandwidth, from 300 MHz up to 15 GHz.

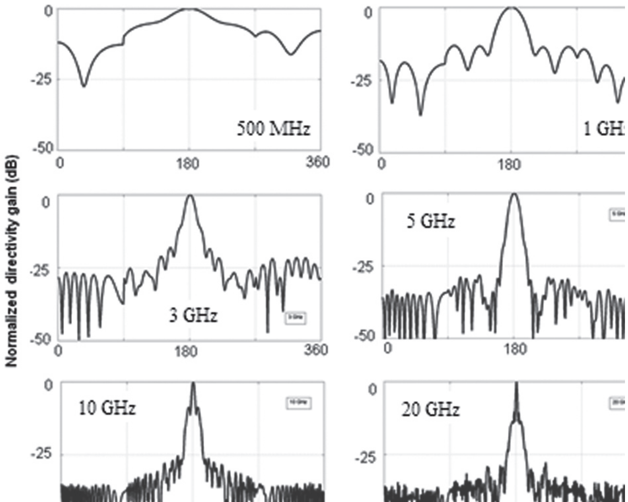

Fig. 5. ARM simulation results of the normalized radiation patterns

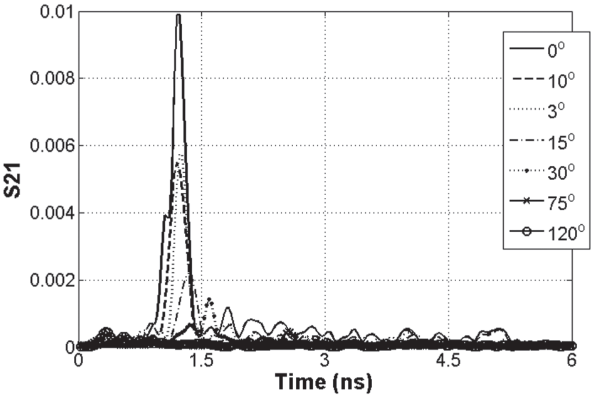

Fig. 6. Time domain transformations of 15 GHz impulse radiation gain measurements for different observation angles

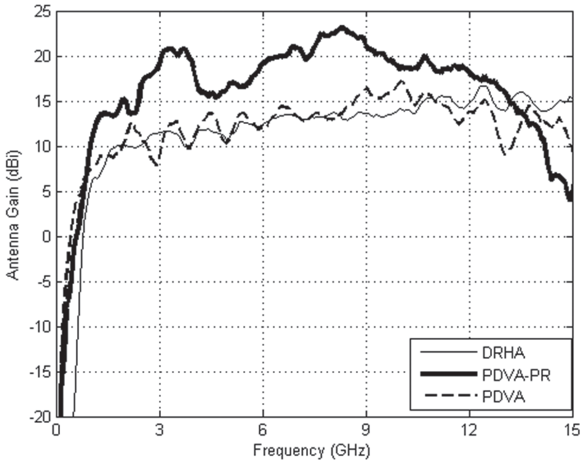

Fig. 7. Antenna gain measurement results; (**Bold**) PDVA fed parabolic reflector, (Solid) 1-18 GHz double ridged horn antenna, (Dashed) PDVA

VI. CONCLUSION

In this study, different design forms of TEM horn antennas, which are dielectric loaded, Vivaldi shaped and array versions, were surveyed for UWB GPR systems. The partial dielectric loaded Vivaldi shaped TEM horn (PDVA) combined with parabolic reflector was introduced to achieve high antenna gain and narrow beam width characteristics over an ultimate wide band greater than 50:1. The PLTLM and ARM algorithms are used to make pre-design of the PDVA-PR in a fast way.

It is shown that antenna attains highly efficient UWB radiation performances, which is suitable for multi-band forward-looking ground-penetrating radar operations.

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Ahmet Serdar Turk received the B.S. degree in Electronics-Communication Engineering from Yıldız Technical University, Istanbul, Turkey in 1996. He received M.S. and Ph.D. degrees in Electronics Engineering from Gebze Institute of Technology, in 1998 and 2001, respectively. He joined the Scientific and Technical Research Council of Turkey (TUBITAK) in 1998. He has worked on land mine detection systems as impulse radar RF system and antenna designer till 2008. He is currently working as professor at Yıldız Technical University Electronics Engineering Department. His research interests include horn, reflector, array and ultra-wide band antenna designs in RF and microwave bands, numerical methods in electromagnetic wave scattering, high frequency surface wave radar, ground penetrating radar, and microwave and millimeter wave radar systems.

Ahmet Kenan Keskin received B.S. degree in Electronics-Communication Engineering from Yıldız Technical University, Istanbul-Turkey in 2010. He is currently working as research assistant at Yıldız Technical University Electronics Engineering Department. His research interests are ultra-wide band antenna design, ground penetrating radar, RF and microwave circuit design.

Mustafa Ilarslan was graduated from the Middle East Technical University of Ankara in 1989, with a B.Sc. degree in Electrical & Electronics Engineering. He served in various TurAF (Turkish Air Force) units at different positions that include avionics maintenance officer, project officer and IFF systems engineer at NATO till 2003. He received M.Sc. degree in Electronics Engineering from the Osmangazi University of Eskisehir, Turkey. He joined the academic staff of TurAF Academy in 2008 and held the positions of Planning Division chief and the head of Electronics Engineering department. He has been the director of Aeronautics and Space Technologies Institute of TurAFA located in Istanbul, Turkey since March 2011. His research interests are aircraft and spacecraft avionics, systems engineering, radar and EW systems and technologies.

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Применение частично заполненных диэлектриком антенн рупорного и рефлекторного типов для сверхширокополосных подповерхностных радиолокаторов / А.С. Турк, А.К. Кескин, М.Иларслан // Прикладная радиоэлектроника: науч.-техн. журнал. – 2013. – Том 12. – № 1. – С. 99–104.

Статья посвящена разработке сверхширокополосных (СШП) ТЕМ-антенн рупорного типа и их использованию в качестве облучателя для параболического отражателя, которые предназначены для установленных на транспортных средствах смотрящих вниз и вперед импульсных георадаров, соответственно. С этой целью были исследованы, сконструированы, промоделированы и измерены частично заполненные диэлектриком антенны Вивальди и конфигурации массива ТЕМ-рупоров. С использованием антенны Вивальди в форме ТЕМ-рупора в качестве облучателя параболической зеркальной антенны предлагается достичь гиперширокой полосы импульсного излучения от 300 МГц до 15 ГГц для работы в составе многодиапазонного георадара, что может обеспечить получение изображения на глубине с высоким разрешением. Усиление и отражение по входу соответствуют результатам измерений.

Ключевые слова: сверхширокополосная антенна, ТЕМ-рупор, параболический отражатель, георадар, импульсное излучение.

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Застосування частково заповнених діелектриком антен рупорного та рефлекторного типів для надширокосмугових підповерхневих радіолокаторів / С. Турк, А.К. Кескін, М.Іларслан // Прикладна радіоелектроніка: наук.-техн. журнал. – 2013. – Том 12. – № 1. – С. 99–104.

Стаття присвячена розробці надширокосмугових ТЕМ-антен рупорного типу та їх використанню як опромінювача для параболічного відбивача, які призначені для встановлених на транспортних засобах таких, що дивляться вниз і вперед імпульсних георадарів, відповідно. З цією метою були досліджені, сконструйовані, промоделювані та виміряні частково заповнені діелектриком антени Вівальді та конфігурації масиву ТЕМ-рупорів. З використанням антени Вівальді у формі ТЕМ-рупора як опромінювача параболічної дзеркальної антени пропонується досягти гіперширокі смуги імпульсного випромінювання від 300 МГц до 15 ГГц для роботи в складі багатосмугових георадарів, що може забезпечити отримання зображення на глибині з високою роздільною здатністю. Посилення і віддзеркалення по входу відповідають результатам вимірювань.

Ключові слова: надширокосмугова антена, ТЕМ-рупор, параболічний відбивач, георадар, імпульсне випромінювання.

Іл. 07. Бібліогр.: 13 найм.