Quadric Resistive Sheet Profile for Wideband Antennas

Zdeněk ŘEZNÍČEK, Zbyněk RAIDA

Dept. of Radio Electronics, Brno University of Technology, Purkyňova 118, 612 00 Brno, Czech Republic

xrezni12@stud.feec.vutbr.cz, raida@feec.vutbr.cz

Abstract. *A new type of a nonreflecting resistive dipole antenna with quadric continuous resistivity profile is presented in this paper. The antenna is mathematically described and compared with the antenna originally proposed by Wu and King. The verification of a proposed theory and the comparison between Wu-King and quadric profile are carried out by simulation models that were designed for this purpose. The attention is turned to the proper attenuation of a wave excited on the resistive sheet, especially.*

Keywords

UWB antenna, resistive sheet, Wu-King profile, time domain, EMC, geophysical tomography.

1. Introduction

Due to the increasing needs for suitable electromagnetic field measurements at higher frequencies (EMC and geophysical tomography, especially), appropriate antennas have to be designed with emphasis on maximum sensitivity and minimum distortion of measured fields.

For these measurements, time domain methods are often used. The transfer function of the antenna, which does not depend on frequency, is one of the most important characteristics of *time-domain* antennas. However, such antennas exhibit several disadvantages (a lower efficiency, e.g.).

Summarizing demands, *time-domain* antennas should be wideband antennas exhibiting good sensitivity, invariant transfer function, and omni-directionality (in most cases).

Most of those characteristics can be achieved by using a resistive dipole which was proposed by Wu and King in 1965 [1]. Later on, the original theory was improved [2] and unified [3] by several researchers.

Unfortunately, the proposed antenna exhibits a limited sensitivity due to the used resistive sheet. In this paper, potential sensitivity improvements of such antennas are discussed modifying the resistive sheet shape along the main dipole axis.

2. Mathematical Considerations

Let us assume a thin wire dipole. The dipole axis is parallel to the x axis of the Cartesian coordinate system. The dipole is placed in free space (vacuum). The excitation gap of the dipole is positioned at the origin of the coordinate system. The antenna is excited by the delta-function generator V_0.

Let us assume the ratio of the vector potential $A_x(x)$ and the current $I(x)$ is approximately constant along the dipole axis. In this case, the vector potential at the antenna surface is

$$A_x(x) = \frac{\mu_0 \psi}{4\pi} I_x(x) \tag{1}$$

where ψ is a coefficient, and μ_0 denotes the permeability of vacuum. Then we obtain one dimensional wave equation

$$\frac{\partial^2 I_x(x)}{\partial x^2} + k^2 I_x(x) - jk f(x) I_x(x) = -\frac{j4\pi k^2}{\omega\mu_0\psi} V_0 \delta(x) \tag{2}$$

where [1]

$$f(x) = \frac{4\pi k}{\omega \mu_0 \psi} z^i(x) = \frac{z^i(x)}{30\psi} \ . \tag{3}$$

Here $z^i(x)$ is the inner impedance of the antenna wire per unitary length, ω denotes angular frequency, and k is wavenumber. Commonly, $f(x)$ is given by [1]:

$$f(x) = \frac{2h}{h - |x|} \ . \tag{4}$$

Here, h is the length of the dipole arm.

If antenna parameters are going to be modified, the inner impedance distribution $z^i(x)$, and consequently the shape of the function $f(x)$, have to be changed. Based on the extensive experimental work, we propose to substitute (4) by the dependency

$$f(x) = \frac{2h}{(h - x)^2} \ . \tag{5}$$

Then the differential equation (2) can be rewritten for $x \neq 0$ into the form

$$\left[\frac{\partial^2}{\partial x^2} + k^2 - \frac{j\,2\,kh}{(h-x)^2}\right] I_x(x) = 0 \; . \tag{6}$$

In the original Wu-King theory, (6) was of the form [1]

$$\left[\frac{\partial^2}{\partial x^2} + k^2 - \frac{j\,2\,k}{h-|x|}\right] I_x(x) = 0 \; , \tag{7}$$

and a solution was expressed as [1]

$$I_x(x) = C(h-|x|)\,e^{-jk|x|} \tag{8}$$

where C is an integration constant. The solution of the ordinary differential equation (6) is given as

$$\begin{aligned} I_x(x) = {} & C_1\sqrt{x-h}\;\; J_{k(x-h)}\left(\sqrt{0.25+j2kh}\right) \\ & + C_2\sqrt{x-h}\;\; Y_{k(x-h)}\left(\sqrt{0.25+j2kh}\right) \end{aligned} \; . \tag{9}$$

Here, $J_k(x)$ and $Y_k(x)$ represent Bessel functions of the first and second kind of order k, C_1 is a constant and $C_2 \approx 0$. In this case, eqn. (9) can be expressed as [5]

$$I_x(x) = C_1\sqrt{x-h}\;\; J_{k(x-h)}\left(\sqrt{0.25+j2kh}\right) . \tag{10}$$

The numerically obtained amplitude and phase of the current distribution at the surface of the resistive dipole is compared to the original Wu-King dipole in Fig. 1 for the antenna of the length h = 120 mm and the radius a = 1 mm. Clearly, there is no current reflection at the end of both the dipoles. On the other hand, the current is more efficiently attenuated in case of the newly proposed solution.

3. Resistive Sheet Characterization

Several researchers extending the Wu-King theory assumed that the impedance distribution along the main dipole axis related to the current distribution (8) was purely real. In [2], validity of the above statement is discussed demonstrating that the inclusion of the parallel inductance together with the resistive load can significantly modify the radiated wave. However, we will discuss this structure at high frequencies only considering $\psi \approx \mathrm{Re}(\psi)$. Then:

$$\mathrm{Im}\left[z^i(x)/\psi\right] \to 0 \; . \tag{11}$$

Then, we can determine the impedance distribution along the dipole axis for the current distribution (10):

$$z^i(x) = \frac{60\,\psi\,h}{(h-x)^2} \cong \frac{R_{sq}\,L^2}{2Y}\,\frac{1}{(L-x)^2} \tag{12}$$

where $2L$ is the length of dipole without the port, Y is the width of the resistive layer used, and R_{sq} is the resistivity of the resistive material per square meter.

According to theory proposed by Kanda and Driver in [3], the new type of the described dipole can be realized as a triangular planar object with a continuously tapered resistive sheet. A conical dipole is another convenient, nonplanar alternative (see Fig. 2). Here, Y represents the circumference at the base of the conical dipole, x = 0 [4].

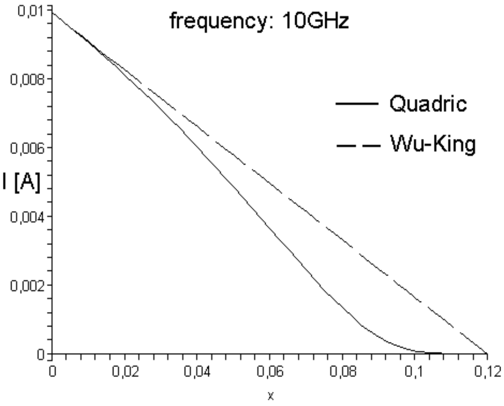

Fig. 1a. Amplitude of the current distribution along the dipole arm.

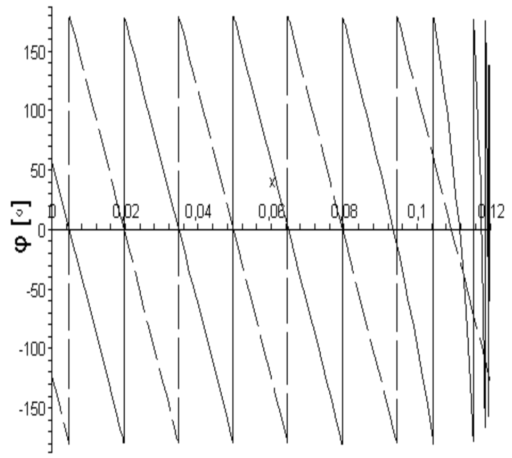

Fig. 1b. Phase of the current distribution along the dipole arm.

4. Verifications

In order to verify the newly proposed impedance distribution, numeric models in CST Microwave Studio (frequency domain differential approach) and Zeland IE3D (frequency domain integral approach) were developed.

4.1 Simulation Model

In this part, the description of simulation model will be given. The way creating the required impedance distribution along the main dipole axis with the port selection will be discussed afterwards.

In CST Microwave Studio, modeling a conical dipole covered by a resistive sheet is rather difficult. By thorough testing in IE3D, a substitution of a conical dipole by a cylindrical one was found as a potential solution in case the dipole is long and thin enough. Differences in simulation results were negligible, and the approximation was sufficient for verification purposes.

Fig. 2 shows the modeled structure. According to the proposed theory, the main axis of the dipole model was set to the z axis. For this particular case, the dipole arm length is $L = 120$ mm, and the radius equals to $r = 1$ mm. The distance between the dipole arms is $p = 4$ mm.

The feeding port was modeled as a discrete port with the 100 Ω impedance load. As shown in [5], Wu-King non-reflecting dipole terminated by 100 Ω loading does not provide very good bandwidth. However, our primary goal is not focused on bandwidth improvements, but on the possibilities of limiting resistivity reduction. Here, the limiting resistivity is the smallest resistivity of resistive sheet R_{sq} that can be used for the dipole with traveling wave only.

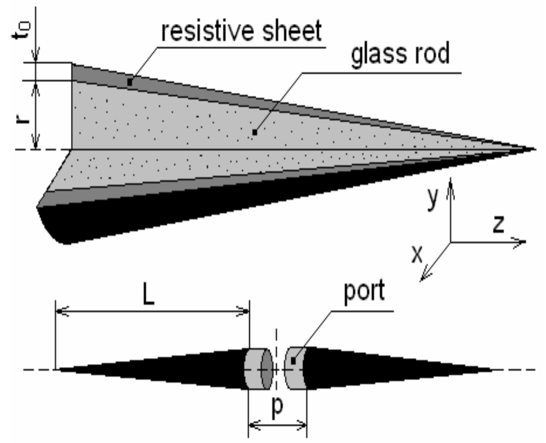

Fig. 2. Graphical representation of the resistive conical dipole model.

The internal impedance distribution along the dipole axis was done by dividing the dipole arm to 60 identical annular surfaces on the glass rod. The total value of the resistivity was assigned for each of these surfaces by

$$R_n = -R_{sq} \frac{L}{2\pi r} \ln\left(1 - \frac{n\,\Delta z}{L}\right) \tag{13}$$

for Wu-King distribution, and

$$R_n = R_{sq} \frac{L}{2\pi r} \frac{n\,\Delta z}{L - n\,\Delta z} \,. \tag{14}$$

for quadric distribution. In (13) and (14), $2L$ is the length of dipole without the port, N is the number of the annular surfaces on the glass rod, n = 1, 2, …, N, r denotes the radius of the first annular surface and Δz is the length of each surface. Finally, R_{sq} denotes the sheet resistivity per square meter given by

$$R_{sq(n+1)} = \left(R_{n+1} - R_n\right) \frac{2\pi r}{\Delta z} \,. \tag{15}$$

The total resistance distribution R of the dipole model is depicted in Fig. 3. Obviously, the quadric distribution can attenuate the traveling wave at the end of the dipole similarly as the Wu-King one. However, the wave propagating along the Wu-King dipole is more attenuated at the beginning. Consequently, we can find such a value of R_{sq} so that the dipole can still behave as a traveling wave structure, but the attenuation is stronger at the end of the dipole in comparison with the Wu-King one.

4.2 Simulation Parameters

In order to analyze the resistive conical dipole in the CST Microwave Studio, the frequency domain solver and the tetrahedral mesh were used due to a thin resistive sheet. Each half of the dipole resistive layer was divided to 60 parallel dodecagons with resistivity values given by (13) or (14). Frequency range was set from 0.5 GHz to 20 GHz, and the accuracy was set to 10^{-6}. In order to avoid meshing problems, the mesh was adjusted manually. The maximum step width of the structure element was set to 0.4.

The IE3D does not allow the cylindrical dipole design based on the resistive sheet on a glass rod, so a standalone resistive sheet was modeled only. Because of this, only simulation results from CST Microwave Studio are presented here.

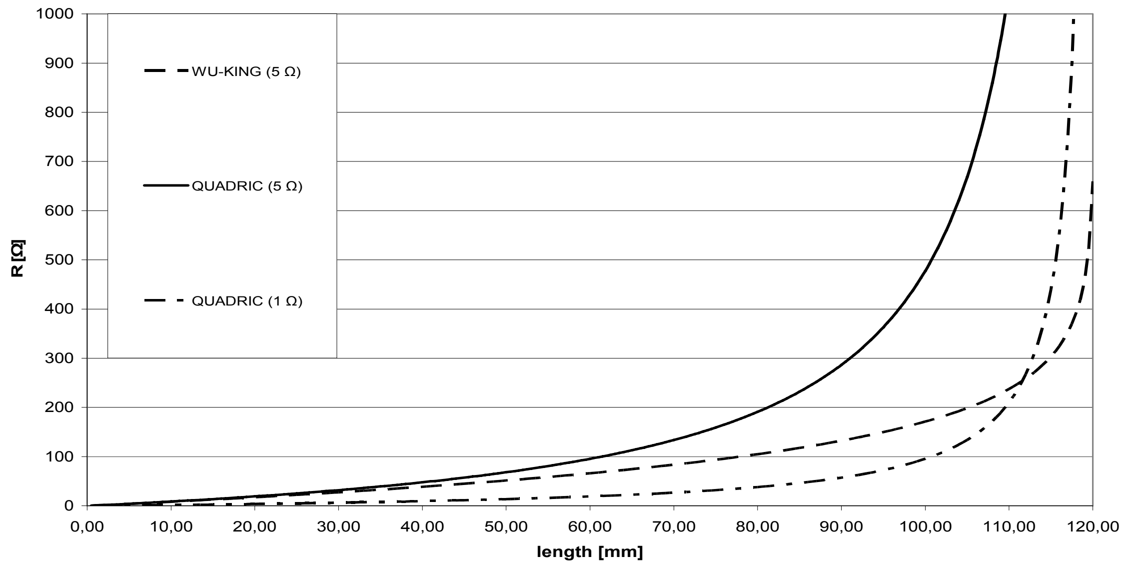

Fig. 3. Shape of the total value of the resistivity along the dipole arm.

4.3 Simulation Results

In this section, a detailed comparison of the quadric resistive sheet dipole and the Wu-King one is provided considering results of numerical modeling.

First, the traveling wave nature of structures is verified. Let us consider a metallic sheet on the dipole instead of the resistive one. Since the current is not attenuated, the return loss S_{11} depends on the reflected wave, and exhibits frequency-dependent interference behavior (the red response in Fig. 6 for the copper sheet). If the metallic sheet is replaced by a resistive one with R_{sq} high enough, the reflected wave is negligible due to the attenuations, and no interference behavior can be seen (the blue response in Fig. 6 for the resistive sheet). We can therefore deduce that the examined structure is the traveling one.

Figures 4 and 5 show the S_{11} frequency response of the resistive dipole; S_{11}–Cu stands for the metallic sheet structure. Responses demonstrate that the limiting resistivity for the Wu-King profile is 5 Ω/□, and for the quadric profile equals to 1 Ω/□, approximately. I.e., the quadric profile is capable to attenuate an excited wave on the resistive sheet with roughly five times smaller resistivity compared to the Wu-King profile in this case.

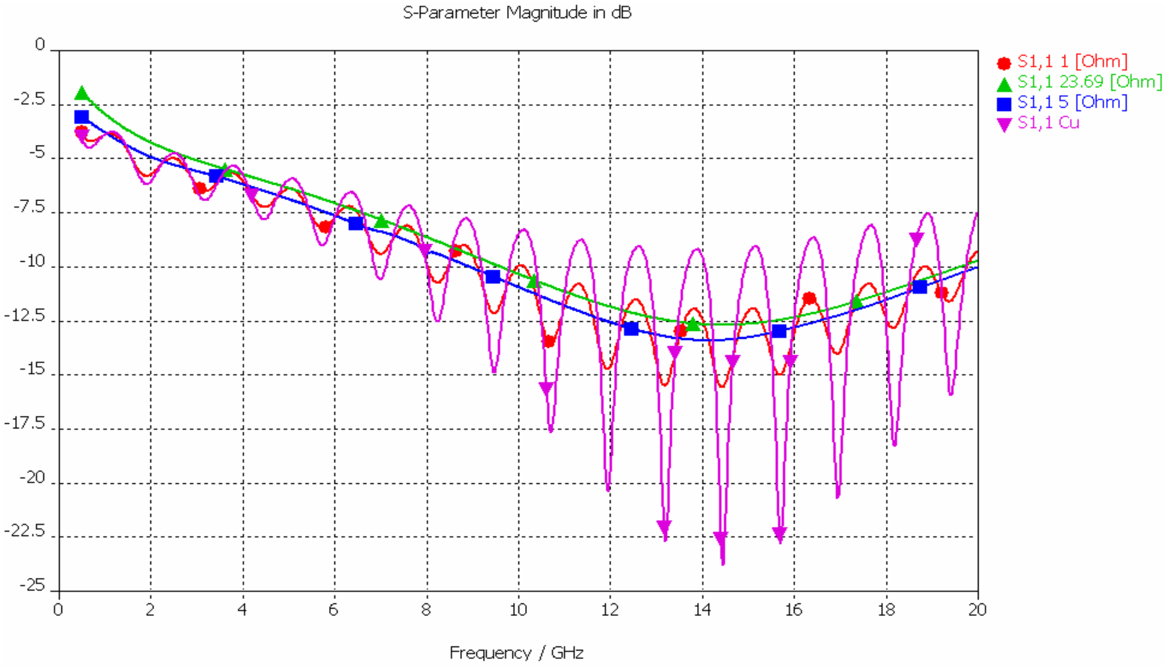

Fig. 4. Frequency response of the reflection coefficient at the input of the Wu-King dipole model.

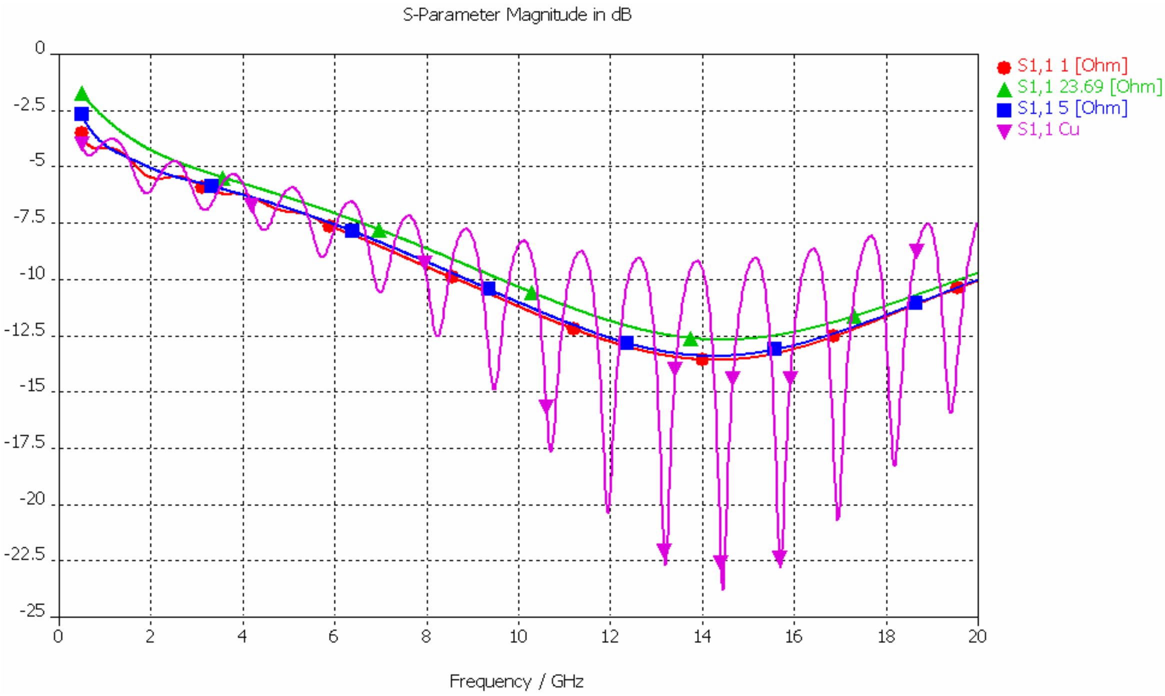

Fig. 5. Frequency response of the reflection coefficient at the input of the quadric dipole model.

In the time domain measurements, the frequency response of the S_{11} phase dependence on frequency is important as well; the response is required to be as linear as possible. Fig.6. shows the phase behavior of S_{11}; it remains approximately linear until the reflected wave appears.

Radiation patterns of the dipoles in the H plane are depicted in Fig. 7. Obviously, the resistive sheet tends to suppress gain deviations. This feature is feasible in case of omni-directional antenna systems, especially [3]. Comparing the gain of the quadric dipole (1 Ω/□) and the Wu-King one (5 Ω/□), the quadric dipole attains even better values of gain in some directions.

5. Conclusion

The paper presents an extended theory of traveling wave resistive dipoles. The formula describing a current distribution along the dipole with a quadric profile of a resistive sheet was derived and compared to the Wu-King one. Antenna simulation models with quadric and Wu-King profiles were designed here to verify the theory.

Simulation results were presented and discussed showing that the quadric profile is capable to replace the Wu-King one in every discussed area.

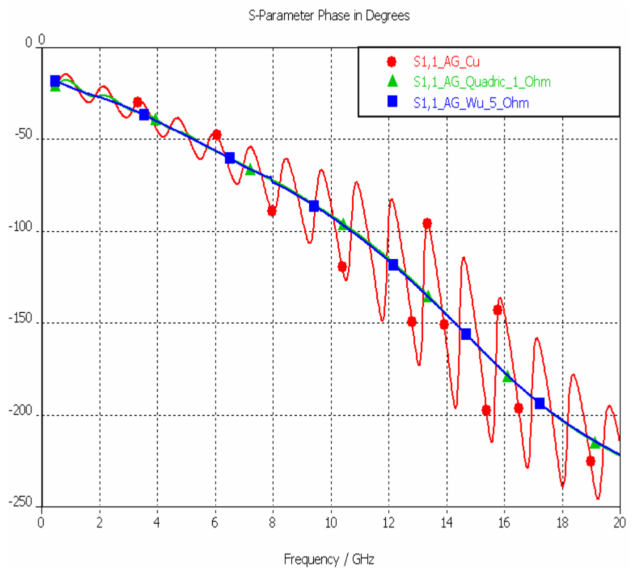

Fig. 6. Phase behavior of S_{11} parameters.

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References

[1] WU, T. T., KING, W. P. The cylindrical antenna with nonreflecting resistive loading. *IEEE Transactions on Antennas and Propagation*, 1965, vol. 13, no. 3, p. 369–373.

[2] WRIGHT, D., PREWITT, J. Radiating dipole antenna with tapered impedance loading. *IEEE Transactions on Antennas and Propagation,* 1975, vol. 23, no. 6, p. 811–814.

[3] KANDA, M., DRIVER, L. D. An isotropic electric-field probe with tapered resistive dipoles for broad-band use, 100 kHz to 18 GHz. *IEEE Transactions on Microwave Theory and Techniques,* 1987, vol. 35, no. 2, p. 124–130.

[4] REZNICEK, Z., RAIDA,Z. Extended theory of Wu-King travelling wave resistive antenna. *Elektrorevue,* Online. www.elektrorevue.cz

[5] ESSELLE, K. P.,STUCHLY, S. S., Pulse-receiving characteristics of resistively loaded dipole antennas. *IEEE Translations on Antennas and Propagation*, 1990, vol. 38, no. 10, p. 1677-1683.

About Authors...

Zdeněk ŘEZNÍČEK was born in Uherské Hradiště, the Czech Republic, in 1981. In 2006, he received Ing. (M.Sc.) degree in Electrical Engineering from the Brno University of Technology. Since 2006, he has been a post-graduate (Ph.D.) student at the Dept. of Radio Electronics, Brno University of Technology.

Zbyněk RAIDA received Ing. (M.Sc.) and Dr. (Ph.D.) degrees from the Brno University of Technology (BUT) in 1991 and 1994, respectively. Since 1993, he has been with the Dept. of Radio Electronics of BUT as the assistant professor (1993 to 98), associate professor (1999 to 2003), and professor (since 2004). From 1996 to 1997, he spent 6 months at the Laboratoire de Hyperfrequences, Universite Catholique de Louvain, Belgium as an independent researcher.

Prof. Raida has authored or coauthored more than 80 papers in scientific journals and conference proceedings. His research has been focused on numerical modeling and optimization of electromagnetic structures, application of neural networks to modeling and design of microwave structures, and on adaptive antennas.

Prof. Raida is a member of the IEEE Microwave Theory and Techniques Society. From 2001 to 2003, he chaired the MTT/AP/ED joint section of the Czech-Slovak chapter of IEEE. In 2003, he became the Senior Member of IEEE. Since 2001, Prof. Raida has been editor-in-chief of the Radioengineering journal (publication of Czech and Slovak Technical Universities and URSI committees).

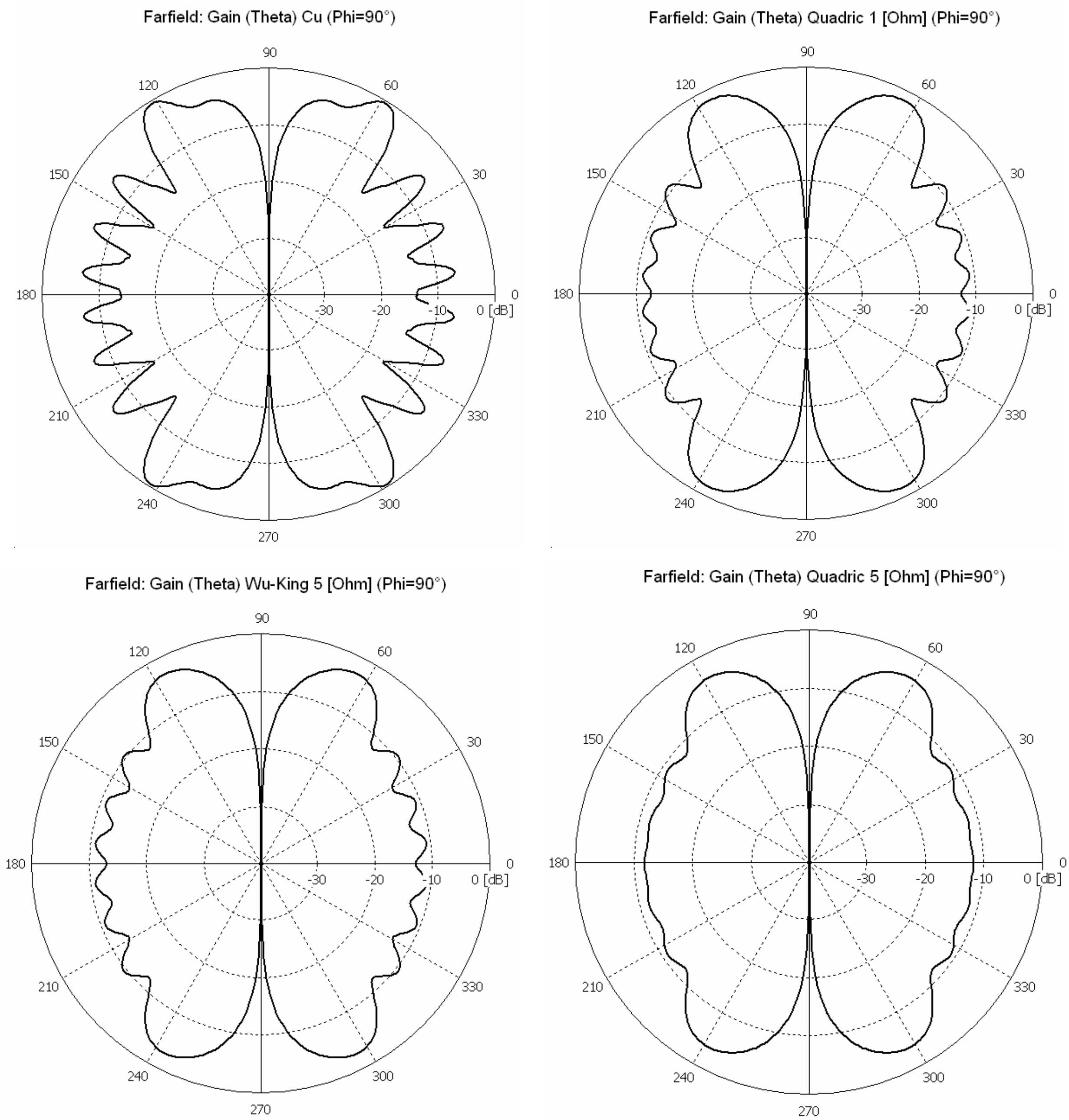

Fig. 7. Graphical representation of the gain versus υ angle (φ = 90°, f = 10,25GHz).