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Matrix Analysis and Pulse Transmission of Antenna Array for MIMO UWB Systems

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***Abstract*—This paper presents a theoretical matrix analysis of antenna structure consisting of two double-element planar antennas for ultra-wideband (UWB) application in 2*2 MIMO indoor communication systems. The structure and characteristics of pla-nar two-element UWB antenna are presented. Two matrix models of MIMO antenna system are represented in the paper. A stan-dard MIMO signal transmission matrix without taking into con-sideration the coupling between antennas is described. A new ap-proach to a full electromagnetic analysis based on the scattering matrix of the MIMO spatial antenna array is proposed. Func-tional power parameters for the whole MIMO UWB transmit-receive antenna structure are introduced. Results of computer si-mulations of different matrices describing a MIMO antenna sys-tem and the transmission propagation pulses are presented.**

***Keywords*—Planar UWB antennas, computer-aided design, ultra-wideband communication, MIMO system.**

I. Introduction

ULTRA-WIDEBAND (UWB) transmission has recently received great attention in both academia and industry for applications in wireless communications [1], [2]. UWB technology became a very interesting solution for many different radiocommunication systems: a medium for high-data-rate links, WPAN and multimedia applications, a sensor, metering, tracking, positioning and medical systems, etc. [3]–[9]. The most interesting approach of the UWB radio system is transmitting and receiving very short electromagnetic pulses which have corresponding spectrum range of a few GHz. In this paper the most important frequency band allowed by FCC for UWB systems 3.1-10.6GHz is considered [1], [2].

It is very important to apply UWB technology for a design of multiport-input-multiport-output (MIMO) radio system. There are many publications describing design methods for different MIMO systems [6]–[10]. The main model described in these papers is a standard MIMO signal transmission matrix widely used for design and analysis of these systems. However, the main disadvantage of such model is that the coupling between separate radiators in transmit and receive antenna array is not taken into consideration. There are no results of the influence of this coupling on the operation of MIMO systems.

The paper presents a new approach to a full electromagnetic design and the analysis of the whole MIMO spatial antenna array with an accurate consideration of the coupling between all radiators in transmit and receive antenna arrays. An electromagnetic model based on the scattering matrix of the whole spatial MIMO UWB antenna system is proposed.

A complex interactive approach was used to design of UWB transmit and receive antennas arrays in frequency band 3.1-10.6GHz [11]–[17]. A mathematical model of functional power parameters for the whole MIMO UWB transmit-receive antenna structure is introduced.

The matrix analysis of the antenna structure consisting of two double-element planar UWB antennas for 2*2 MIMO systems is performed. Structure and frequency characteristics of planar two-element UWB antenna for different frequencies are presented.

There are also shown the results of computer simulations of different matrices, power parameters describing the whole MIMO UWB antenna system and the transmission propagation pulses in the system.

II. Structure and Characteristics of Planar Two-Element UWB Antenna

The structure and dimension (in mm) of the designed double-element UWB antenna is presented in Fig. 1a. The whole structure of 2*2 MIMO UWB antenna structure consisting of two double-element UWB antennas and propagation space between them (marked by dotted lines) is shown in Fig. 1b.

Each planar two-element UWB antenna consists of two equal elliptical radiators with three-section optimal matching transformers placed on common dielectric, $\epsilon_r = 2.2$.

Both elements have the same ground plane on the other side of dielectric with dimensions: 66*16mm. A few variants of the antenna array for different distances between radiators were considered and calculated – in this paper one specific model for the distance of 10mm is discussed. All characteristics were calculated in FCC UWB frequency band 3.1-10.6GHz.

A special design algorithm was proposed to design a single planar UWB antenna composed of a single elliptical radiator and its matching transformer realized by transmission line [11]. There are a few steps in the design procedure of such antennas. There was an assumption that main dimensions of the antenna are known: dimensions of elliptical radiator (32*25mm) and backside ground plane.

Firstly, the impedance Z_{in} of alone elliptical radiator with only back ground plane metallization, without microstrip transformer, was calculated. Then, the network three-step microstrip transformer was designed in the network simulator DIASP as an optimal matching circuit for the previously

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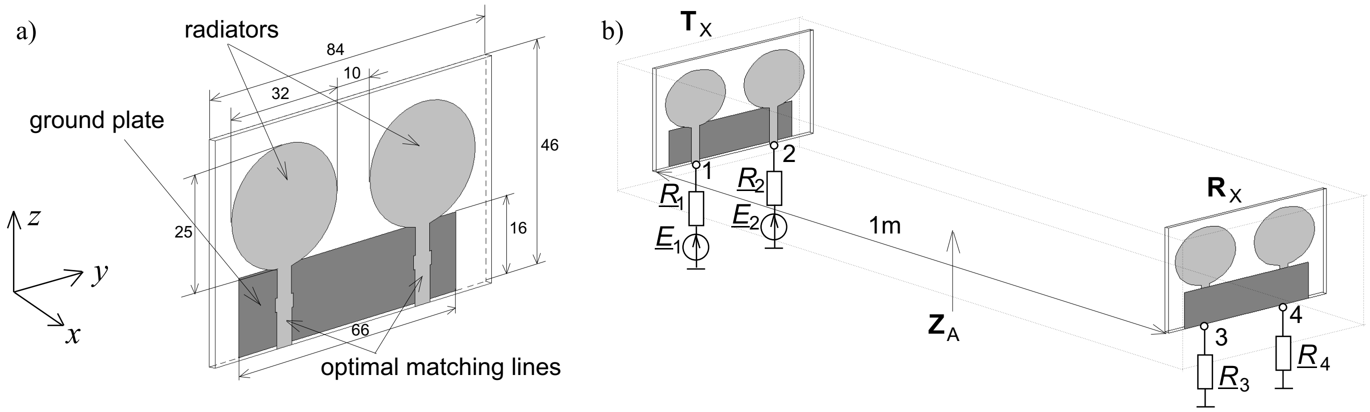

Fig. 1. Structure and dimensions of two-element UWB antenna a), MIMO UWB antenna structure b).

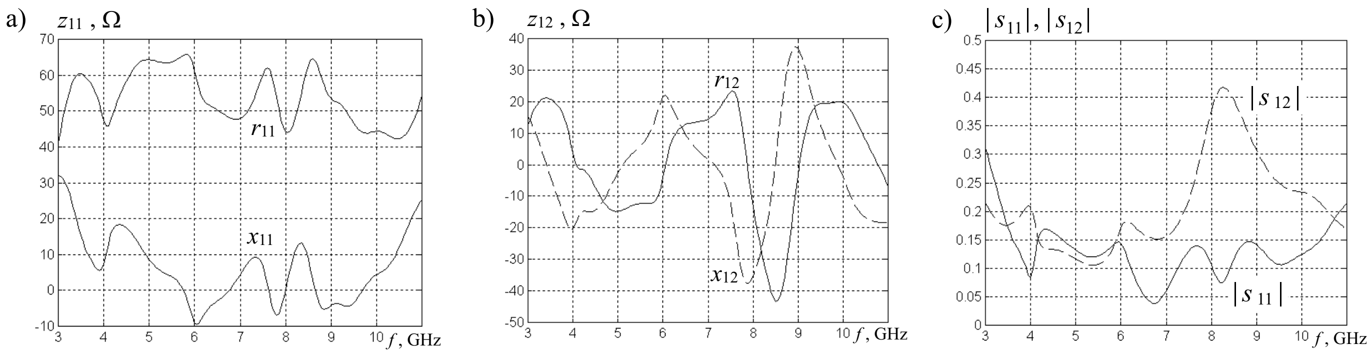

Fig. 2. Elements of impedance a), b) and scattering c) matrices of two-element UWB antenna.

calculated impedance Z_{in} and generator's resistance 50Ω, so a mixed network and electromagnetic model of the antenna was obtained. Then the designed matching transformer was implemented in a full electromagnetic model of the UWB antenna. The last step was an electromagnetic optimization of the whole antenna structure, very close to final structure.

The designed two-element antenna is symmetrical array, so its impedance and scattering matrices are as follows:

$$\mathbf{Z}_{\mathrm{A}}(j\omega) = \begin{bmatrix} z_{11} & z_{12} \\ z_{12} & z_{11} \end{bmatrix}, \quad \mathbf{S}_{\mathrm{A}} = \begin{bmatrix} s_{11} & s_{12} \\ s_{12} & s_{11} \end{bmatrix} \qquad (1)$$

where elements z_{11} and s_{11} represent the impedance and the reflection coefficient determining a matching of a single UWB antenna, z_{12} and s_{12} – the coupling (the mutual impedance and the normalized voltage transmissions) between radiators in UWB double antenna (Fig. 1a).

The correlation between the scattering matrix $\mathbf{S}_{\mathrm{A}}$ and impedance matrix $\mathbf{Z}_{\mathrm{A}}$ is:

$$\mathbf{S}_{\mathrm{A}} = \mathbf{R}^{-0.5}(\mathbf{Z}_{\mathrm{A}} - \mathbf{R})(\mathbf{Z}_{\mathrm{A}} + \mathbf{R})^{-1}\mathbf{R}^{0.5}. \qquad (2)$$

where $\mathbf{R}$ – diagonal resistive matrix of generator's impedance and loads (Fig. 1b).

Both matrices have the same real orthogonal eigenvectors and similar formulas for the eigenvalues $(z_{1,2}, s_{1,2})$:

$$\mathbf{V} = [\mathbf{V}_1\mathbf{V}_2] = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}, \quad \begin{matrix} z_{1,2} = z_{11} \pm z_{12} \\ s_{1,2} = s_{11} \pm s_{12} \end{matrix} \qquad (3)$$

The eigenvectors of two-port symmetrical network describe in-phase and anti-phase excitations. In this case the eigenvalues of all matrices are the sum or the difference of diagonal and non-diagonal elements of corresponding matrices (1, 3).

Elements of impedance matrix of two-element antenna are shown in Fig. 2a, 2b. Non-diagonal elements (mutual impedance) have quite large maximal values, about ±40Ω and for the other analyzed distances between radiators (5-15mm) this value is almost the same. Element's modules of the scattering matrix are presented in Fig. 2c. We can see that this double-element UWB antenna is well-matched in the whole UWB frequency band and it has a large coupling between elements.

Further analysis of a planar two-element UWB antenna concerns its radiation and a near electric field distribution calculated for different excitations at different frequencies. The property of emission of UWB signals may be used for some radiolocation or positioning applications. While the distribution of the near electric field clearly shows the influence of each part of array on summary radiation of the whole UWB antenna.

III. Matrix Analysis of MIMO UWB Antenna System

Mathematical models and matrix analysis of characteristics and parameters of whole MIMO UWB antenna system consists of two double-element antennas is considered (Fig. 1b).

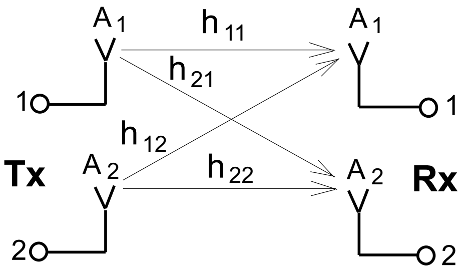

Fig. 3. Standard 2*2 MIMO antenna – signal structure.

Two matrix models of this MIMO UWB antenna system are described in this paper. *At first*, there is presented a known MIMO signal transmission matrix without taking into consideration the coupling between antennas [5]–[8]. *Secondly*, the electromagnetic model based on the scattering matrix of the whole MIMO UWB antenna system is proposed [16], [17].

A. *Usual Signal Transmittance Matrix of MIMO System*

In this case the signal transmission functions from one transmit antenna element to another receive antenna element, used for a description of MIMO channel only, as it is shown in Fig. 3 for two-order antenna arrays [5]–[10].

Generally, the MIMO channel with m transmit and n receive antennas, the input-output relationship between the **Tx** (transmit array) and **Rx** (receive array) is expressed as [10]:

$$\mathbf{Y} = \mathbf{HX} + \mathbf{N}, \tag{4}$$

where **X** is the $[m$ x $1]$ transmitted vector, **Y** is the $[n$ x $1]$ received vector, **N** is the receive additive white Gaussian noise vector, and **H** is $[n$ x $m]$ the channel matrix. For [2 x 2] the MIMO channel, **H** can be written as (Fig. 3)

$$\mathbf{H} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix}, \tag{5}$$

where elements h_{ij} represent the frequency depended transfer functions between j-th transmit and i-th receive antenna element (Fig. 3). In that way, it is proposed that each receive antenna element obtains *different information signals* from each transmit antenna element.

However the coupling between antenna elements (both transmit or receive) is not taken into consideration in this model. Analyzing the coupling between antenna elements, we can see that each transmit antenna element propagates *all information signals* with its different distortion.

B. *Scattering Matrix for MIMO Antenna System*

A mathematical model of the MIMO UWB antenna system based on scattering matrix of the whole antenna structure is considered. This model allows accounting the coupling between all elements of the whole system (Fig. 1b).

For the considered MIMO UWB antenna structure orders of matrices is four and due to symmetry of the whole antenna system impedance and scattering matrices have the same double symmetric structure:

$$\mathbf{Z}_\mathrm{A}(j\omega) = \begin{bmatrix} z_{11} & z_{12} & z_{13} & z_{14} \\ z_{12} & z_{11} & z_{14} & z_{13} \\ z_{13} & z_{14} & z_{11} & z_{12} \\ z_{14} & z_{13} & z_{12} & z_{11} \end{bmatrix},$$

$$\mathbf{S}_\mathrm{A} = \begin{bmatrix} s_{11} & s_{12} & s_{13} & s_{14} \\ s_{12} & s_{11} & s_{14} & s_{13} \\ s_{13} & s_{14} & s_{11} & s_{12} \\ s_{14} & s_{13} & s_{12} & s_{11} \end{bmatrix}, \tag{6}$$

then, as for (1), elements z_{11} and s_{11} represent impedance and matching of a single UWB antenna, z_{12} and s_{12} – the coupling between radiators in UWB double antenna (Fig. 1a), z_{13} , z_{14} , s_{13} and s_{14} – propagation properties between the transmit UWB antenna array and receive one (Fig. 1b). In the matrices (6) equal elements have the same designation. Thus due to symmetrical properties of the MIMO antenna system corre-sponding matrices (6) have four different elements only.

Elements of the scattering matrix $\mathbf{S}_\mathrm{A}$ may be calculated by:

$$\begin{cases} s_{ii} = (Z_i - R_i)(Z_i + R_i)^{-1} = 1 - 2V_i/E_i \\ s_{ji} = 2U_j/E_i\sqrt{R_i/R_j} \end{cases}, \tag{7}$$

where Z_i – input impedance of one antenna element when the rest radiators are terminated by the resistors. We can see that two non-diagonal elements of the scattering matrix $\mathbf{S}_\mathrm{A}$ (6) may be used as elements of a signal transmittance matrix **H** (5). For example, for 2*2 MIMO channel (Fig. 1b) and equal terminated resistors $R = R_i$ we have:

$$s_{13} = 2U_3/E_1 = 2h_{11} = 2h_{22},$$
$$s_{14} = 2U_4/E_1 = 2h_{12} = 2h_{21}. \tag{8}$$

In that way, the scattering matrix $\mathbf{S}_\mathrm{A}$ (6) allows for frequency matching of antennas, the coupling between elements of transmit and receive antenna array and the signal transmission in the whole MIMO radio channel.

The total normalized power absorbed by the whole four element antenna MIMO structure (Fig. 1b) for arbitrary excitation vector **a** is given by normalized hermitian form (Rayleigh ratio) [12], [13]:

$$\frac{P_{ant}}{P_{\max}} = \frac{\mathbf{a}^+\mathbf{a} - \mathbf{b}^+\mathbf{b}}{\mathbf{a}^+\mathbf{a}} = \frac{\mathbf{a}^+(\mathbf{1} - \mathbf{S}_\mathrm{A}^+\mathbf{S}_\mathrm{A})\mathbf{a}}{\mathbf{a}^+\mathbf{a}} = \frac{\mathbf{a}^+\mathbf{D}_\mathrm{A}\mathbf{a}}{\mathbf{a}^+\mathbf{a}}, \tag{9}$$

where $\mathbf{D}_\mathrm{A} = \mathbf{1} - \mathbf{S}_\mathrm{A}^+\mathbf{S}_\mathrm{A}$ – ***dissipation*** matrix of the antenna array; superscript (+) denotes the *hermit conjugate* matrix. It is ***hermitian*** matrix $\mathbf{D}_\mathrm{A} = \mathbf{D}_\mathrm{A}^+$ and *unitary similar* to diagonal positive real matrix of its eigenvalues d_i:

$$\mathbf{D}_\mathrm{A} = \mathbf{V}\{d_i\}\mathbf{V}^+, \; 0 < d_i = d_i^* < 1, \; \mathbf{V}\mathbf{V}^+ = \mathbf{1}, \tag{10}$$

where **V** – complex *unitary* matrix (*modal*) of all *eigenvectors* of the dissipation matrix $\mathbf{D}_\mathrm{A}$.

For *ideal* matching of the arbitrary antenna array:

$$\mathbf{Z}_\mathrm{A} = \mathbf{R}, \; \mathbf{S}_\mathrm{A} = 0 \; \mathbf{D}_\mathrm{A} = \mathbf{1}, \; P_{ant} = \mathbf{a}^+\mathbf{a} = P_{\max} \tag{11}$$

It is known that the normalized total power $P_{ant}/P_{\max}$ is limited by the *minimum* and the *maximum* eigenvalues of the dissipation matrix [12], [13]:

$$d_{\min} \leq \mathbf{a}\mathbf{D}_\mathrm{A}\mathbf{a}/\mathbf{a}^+\mathbf{a} \leq d_{\max} \tag{12}$$

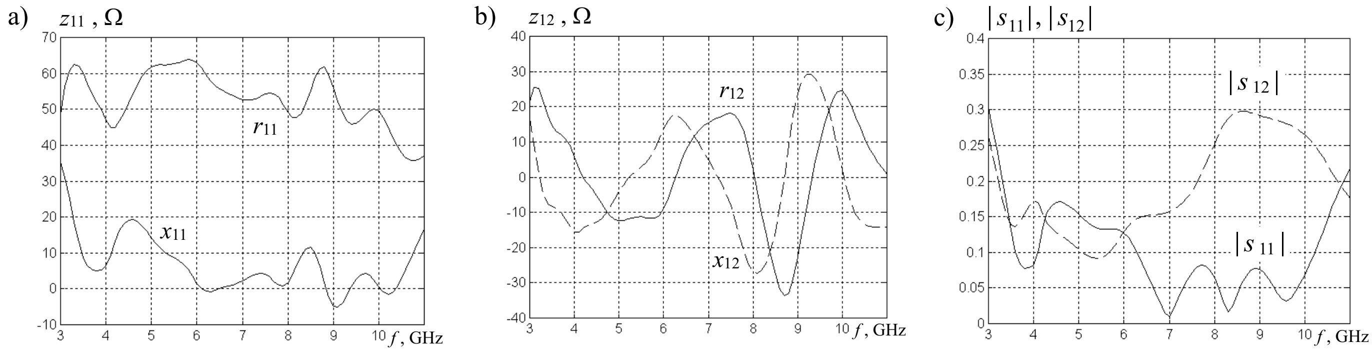

Fig. 4. Elements of impedance a), b) and scattering c) matrices of MIMO UWB antenna system.

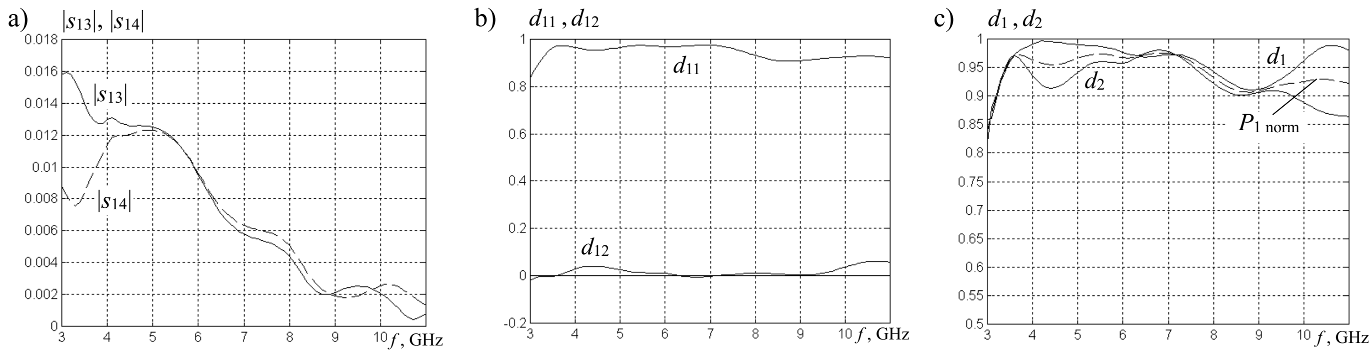

Fig. 5. Elements of scattering a) and dissipation matrices b); eigenvalues of the dissipation matrix of MIMO UWB antenna system c).

Then power optimization and matching problem of the whole MIMO antenna structure for arbitrary excitation vectors reduce to maximization of minimum or maximum eigenvalues of the dissipation matrix $\mathbf{D}_{\mathrm{A}}$ at the given frequency band.

All matrices ($\mathbf{Z}_{\mathrm{A}}$, $\mathbf{S}_{\mathrm{A}}$ and $\mathbf{D}_{\mathrm{A}}$, have the same double symmetric structure, the same orthogonal eigenvectors and similar formulas for the eigenvalues ($z_{1,2,3,4}, s_{1,2,3,4}, d_{1,2,3,4}$):

$$\mathbf{V} = [\mathbf{V}_1\mathbf{V}_2\mathbf{V}_3\mathbf{V}_4] = \frac{1}{2}\begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \end{bmatrix} \quad (13)$$

for example, the eigenvalues for dissipation matrix:

$$d_{1,2} = d_{11} \pm d_{12} + d_{13} \pm d_{14}, \; d_{3,4} = d_{11} \pm d_{12} - d_{13} \mp d_{14} \quad (14)$$

This matrix model and the introduced parameters are used for electromagnetic computer analysis of MIMO UWB antenna structure.

IV. Computer Analysis of Frequency Characteristics of MIMO UWB Antenna System

A computer model of the complete 2*2 MIMO antenna structure shown in Fig. 1b was created in IE3D software. Both identical transmit and receive double-element antennas were placed at a distance of 1m from each other, one exactly opposite another. Double-element antennas are facing each other with their front side (side with radiators and matching lines). A computer simulation was performed in UWB frequency band 3-11GHz using a method of moments (MoM). The whole electromagnetic model was divided into over 2000 cells, 1800 volumes; the number of unknowns required for simulation was about 10000.

Frequency characteristics of the impedance matrix $\mathbf{Z}_{\mathrm{A}}$ elements are shown in Fig. 4a, 4b. Due to using optimal excitation lines connected to each UWB radiator all antennas have a good matching in the given frequency band (VSWR<2.0). We can see that each UWB double-element antenna has a large coupling between the antenna radiators.

Some differences between frequency characteristics of elements z_{11} and z_{12} of single double-element antenna (Fig. 2a, 2b) and these elements for four-port MIMO UWB antenna structure (Fig. 4a, 4b) are explained by different number of cells in both antenna structures (Fig. 1a, 1b) and limited memory of the used computer.

The obtained frequency characteristics of the impedance matrix $\mathbf{Z}_{\mathrm{A}}$ elements were used for calculation of the elements of scattering matrix $\mathbf{S}_{\mathrm{A}}$ (2, 6). These frequency characteristics of the scattering parameters were fulfilled using MATLAB environment according to the proposed mathematical model. The corresponding computer simulation results are shown in Fig. 4c, where $|s_{11}|$ means the matching of each radiator, $|s_{12}|$ – the coupling between radiators in transmit and receive double-element antennas and in Fig. 5a, where $|s_{13}|$ and $|s_{14}|$ mean the signal coupling between each pair of antenna ports of the analyzed UWB radio link.

Frequency characteristics of scattering elements $|s_{11}|$ and $|s_{12}|$ for the single double-element antenna and the whole MIMO UWB antenna structure are very similar, but there is a difference, as for impedance matrix $\mathbf{Z}_{\mathrm{A}}$.

We can see that non-diagonal elements $|s_{13}|$ and $|s_{14}|$ for a distance of 1m between transmit and receive antennas have small values in the entire frequency bandwidth (from 0.016 to 0.001). It can be noticed that non-diagonal s_{12} of scattering matrix $\mathbf{S}_A$ have significant values. It is a normal behavior because of the distance between each antenna in a considered structure.

In connection with proposed theoretical base, frequency characteristics of elements and eigenvalues of the dissipation matrix $\mathbf{D}_A$ for the considered MIMO system were also calculated. It is seen in Fig. 5b that all non-diagonal elements of matrix $\mathbf{D}_A$ have small values in the entire bandwidth. Additionally, the difference between elements of dissipation matrix d_{13} and d_{14} is quite small. Thus, taking into consideration formula (14) frequency characteristics of eigenvalues d_1, d_2 and d_3, d_4 are almost similar. It can be easily proven that total normalized average power is limited by eigenvalues d_1 and d_2 and almost similar for arbitrary excitation vector.

For example, with excitation of the first port of a transmit two-element antenna only (Fig. 1b) normalized input power of the whole antenna MIMO structure P_{1norm} is limited by:

$$d_{\min} \le P_{1norm} = P_1/P_{\max} = 1 - |s_{11}|^2 \le d_{\max} \qquad (15)$$

where $|s_{11}|$ is the element of scattering matrix $\mathbf{S}_A$ (Fig. 6c). All frequency characteristics (15) are shown in Fig. 5c.

Results of the computer simulation of the frequency characteristics and parameters of the whole MIMO UWB antenna structure allow analyze the transmission propagation pulses in the considered system.

For example, in the next section the transmission of UWB pulses is considered with the excitation of the first port of the whole MIMO antenna system only with limitation of input normalized antenna power (15), (Fig. 5c).

V. Transmission of UWB Pulse Signals in the MIMO Antenna System

The transmission of UWB signals in a 2*2 MIMO antenna system was analyzed and the results are briefly shown in this paper. An algorithm for transmission propagation pulse analysis in the antenna system is described in [15], [17].

The antenna marked as 1 in Fig. 1b was excited only with a modulated PPM with randomization train of UWB Gaussian pulses E_1 (Fig. 6a) and the output voltages $U_2 - U_4$ were calculated. This is the same example considered in the previous section (15) (Fig. 5c). To calculate the output pulse shapes in the analyzed system is necessary to know a transmittance between the port number 1 and all other ports (Fig. 4, 5). Such transmittances were defined as half of the values of the corresponding non-diagonal parameters of the scattering matrix (7, 8). For example elements s_{21} and also s_{12} of the antenna structure are given by:

$$s_{21} = \sqrt{\frac{R_1}{R_2}}\frac{2U_2}{E_1} \qquad (16)$$

Assuming that all resistors connected to all MIMO system ports are the same and equal 50Ω to calculate the output signals U_2 in the port number 2, while generator is connected to port number 1, the transmittance (U_2/E_1) equals half of

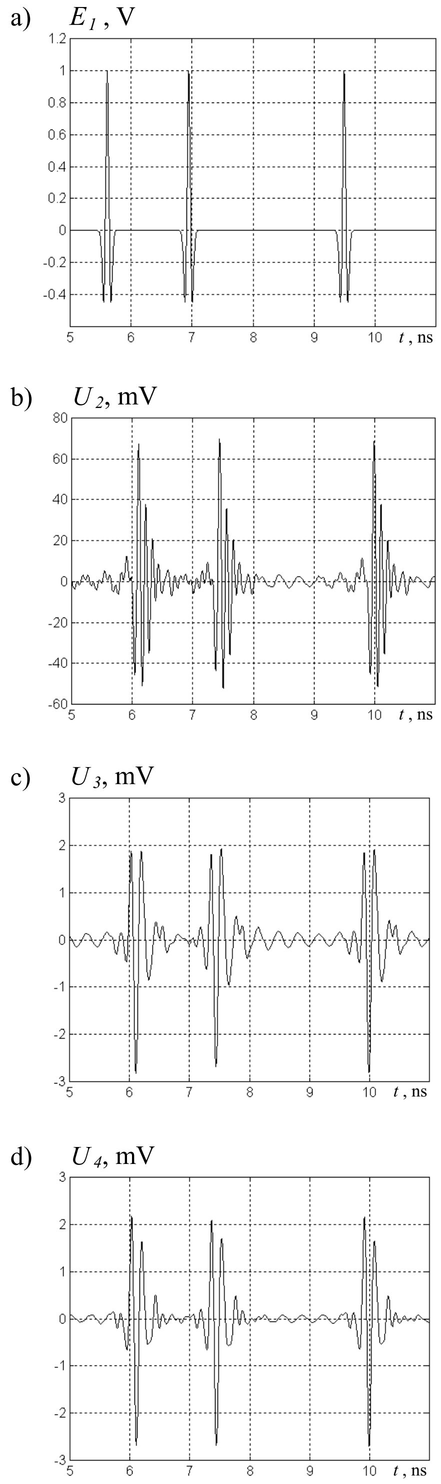

Fig. 6. Pulse propagation in MIMO UWB antenna system.

the value of s_{21} element. The same procedure is valid for calculation of transmittance between all the other ports of MIMO antenna system.

The transmittance calculated in presented way was then multiplied in the frequency domain by the spectrum of the input signal E_1 and reverse Fourier transformation was applied to obtain the output signal U_2 in time domain. Voltage U_2 and other output signals U_3 and U_4 were calculated in the same way as shown in Fig. 6b-6d. There are different propagation delays between all analyzed ports in this case, so all output pulses were artificially shifted in time domain to be placed in the same moments. The following pulses shown in Fig. 6b-6d have different shapes and amplitudes. The amplitudes of signals U_3 and U_4 are more or less the same, but those of U_2 are very significant.

It is a proof that the mutual coupling between transmitting and receiving elements in MIMO systems cannot be omitted. Such received pulses U_3 and U_4 are the results of propagation of both radiators (A_1 and A_2) of the transmit double-element UWB antenna with the same information signals and some distortion of the signal U_2. The received pulses are quite clearly distinguished, so their separation using space-time codes would not be a problem.

VI. Conclusions

This paper presents theoretical matrix analysis of the antenna structure consisting of two (transmit and receive) double-element planar antennas for ultra-wideband (UWB) application in 2*2 MIMO indoor communication systems. The structure, frequency characteristics, radiation patterns and a distribution of the near electric field of the planar two-element UWB antenna are presented. A complex interactive approach was used to design of UWB transmit and receive antennas arrays in frequency band 3.1-10.6GHz. A mathematical model of functional power parameters for the whole MIMO UWB transmit-receive antenna structure is introduced.

Two matrix models of MIMO antenna system are represented in the paper. A standard MIMO signal transmission matrix without taking into consideration the coupling between antennas is described. A new approach to full electromagnetic analysis based on the scattering matrix of the whole MIMO spatial antenna array is proposed.

This model allows the frequency matching of antennas, the coupling analysis between elements of transmit and receive antenna arrays and the signal transmission in the whole MIMO radio channel.

The results of computer simulations of different matrices describing the whole MIMO UWB antenna system and transmission propagation pulses in the system are presented.

The obtained results represent the first stage in the investigation of the propagation of signal properties in the MIMO UWB antenna systems with a consideration of the electromagnetic coupling between all elements of this system. The proposed methods may be used for designing new modern radiocommunication systems.

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