RECONSTRUCTION OF THE OBJECTS IMAGES BY THE DIFFRACTION TOMOGRAPHY METHOD ON MICROWAVE AND MILLIMETER WAVES

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Abstract

On the base of TUJRL experience in the field of microwave and millimeter wave technologies, development of microwave and millimeter wave tomography for nondestructive testing and subsurface investigations is suggested. It may be manufactured as well in waveguide modification as in quasioptical one. Description of the main principles of creation of the tomographic system both for millimeter wave band and for microwaves is given below. The system combines possibilities as well of tomograph operating "on passage" as tomograph operating in regime of undersurface measurements. Using both of these approaches will allow us to create microwave or millimeter wave tomograph providing the image reconstruction of the object under investigation.The suggesting version of tomography is orientated towards applications in industry, medicine, detection and identification of abandoned objects and other fields.

1. Introduction

The electromagnetic diffraction tomography systems are already in use for some industrial, scientific and medical applications [1-3]. The first research activity was influenced by the works of Larsen and Jacobi [1]. In comparison to other imaging techniques (x-rays, NMR (nuclear magnetic resonance), ultrasonic) electromagnetic waves as partially confirmed by preliminary evaluations, offer good sensitivity, convenient compatibility with equipment, and moderate cost. In addition, they allow permanent monitoring and their low irradiation levels make them innocuous.

An industrial application of the diffraction tomography system is the testing of materials and manufactured article. The problem consist of detecting and localising inhomogeneities and, finally, of estimating their diameters. For example, X-band linear microwave sensor is designed for the control of conveyed products. The translation of the product or material under test, combined with a rapid transversal multipoint analysis, allows one to obtain the microwave image of products moving at speeds as fast as a few meters per second. Such a linear sensor allows one to measure the local reflection and/or transmission coefficients of different materials which are assumed to be representative of some property of this material (humidity, local defect, roughness). In this way, it opens the way to real-time transverse control of paper humidity during drying processes, detection of defects in wooden boards in view of sawing optimisation, and quality control of laminated/composite layers. In such applications, the required resolution is of 1 cm.

Possibilities of the first-order diffraction tomography in the case of using of millimeter electromagnetic waves for object sounding (quasioptical tomography) do not studied well. There are difficulties in measurement of amplitude and phase of the scattered field in millimeter waves. On the other hand, application of millimeter waves in diffractional tomography may sufficiently increase its possibilities. For example, increasing of sounding radiation frequency gives us possibility to get Fourier image of the object investigated at higher spacial frequencies and, therefore, to improve quality (resolution) of the tomographic image.

2. Diffraction Tomography Principles

The basic equation of the diffraction tomography may be obtained as a result of solution of a scattering inverse problem of a plane electromagnetic wave by the object under investigation. We consider an object characterising by refractive index $n(\vec{r}) = 1 + n_{\delta}(\vec{r}) \equiv 1 + f$, where f is equal to zero outside the refracting object. Incident plane harmonic ($\exp(-i\omega t)$) wave $U_I(\vec{r}) = \exp[ik(\vec{\theta} \cdot \vec{r})]$ is scattered by the object; $\vec{\theta}$ is a unit vector pointing the direction of the wave propagation; $k = \omega / c$; ω is radiation frequency; c is light velocity. In the case of direct scattering, the total field $U = U_I + U_S$ (where $U_S(\vec{r})$ is a scattered wave) satisfies the given wave equation

$$\Delta U + k^2 (1 + f)^2 U = 0 \tag{1}$$

and the boundary condition in infinity (Δ is Laplasian). The scattered field U_S may be found using equation (1) in the first-order Born approximation. So, for the scattered field $U_S^{(1)}(\vec{r})$ may be written in integral form:

$$U_S^{(1)}(\vec{r}) = \int G(\vec{r} - \vec{r}\,')Q(\vec{r}\,')U_I(\vec{r}\,')d\vec{r}\,' \tag{2}$$

where $G(\vec{r} - \vec{r}\,') = (i/4)H_0^{(1)}(k\,|\,\vec{r} - \vec{r}\,'\,|)$ is a Green function; $H_0^{(1)}$ is Hankel function of the first type of zero order; $Q(\vec{r}) = k^2(2f + f^2)$. The integral representation (2) of the scattered field $U_S^{(1)}(\vec{r})$ is permitted under the following condition $U_S << U_I$.

In inverse scattering problem, function f should be find with known scattered field U_S. Solution of such problem using relations' (2) allows us to obtain the main equation of diffraction tomography [2, 4]. After we may find functions $Q(\vec{r})$ and $f(\vec{r})$, if we know (after calculations or experimental results) $U_S^{(1)}$ or $U_I(k\Phi_R)$.

3. The Subsurface Diffraction Tomography

In this part we will briefly consider our approach to the image processing in subsurface diffraction tomography. The scattered field $\psi(x, y_1)$ at line $y = y_1$ (1-D case, Fig.1) can be represented in the form of Fourier integral

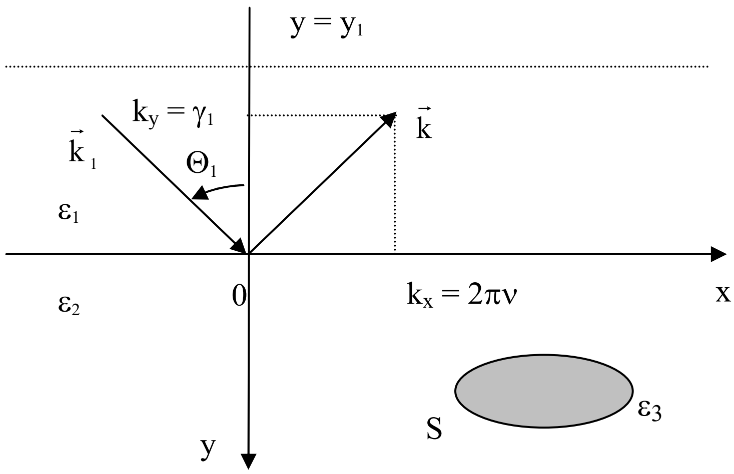

Fig.1. The region under consideration in plane x, y and projections of wave vector on the axes of reference

$$\psi(x, y_1) = \int_{-\infty}^{\infty} \hat{\psi}(\nu, y_1) \exp(2\pi i x \nu) d\nu \qquad (3)$$

where $\hat{\psi}(\nu, y_1)$ the Fourier image of $\psi(x, y_1)$ and it is defined as

$$\hat{\psi}(\nu, y_1) = \varphi(\nu) \exp\left[-i y_1 \sqrt{k^2 - (2\pi\nu)^2}\right] = \varphi(\nu) \exp(-i \gamma_1 y_1) \qquad (4)$$

$\gamma_1 = \sqrt{k^2 - (2\pi\nu)^2}$; $k = (\omega / c)$ is wave number of plane wave in free space; ω is cyclic frequency; c is velocity of light. Function $\varphi(\nu)$ can be written as

$$\varphi(\nu) = c_1(\nu) c_2(\nu) \qquad (5)$$

where

$$c_1(\nu) = \frac{i k_2^2 T}{\gamma_1 + \gamma_2} \qquad (6)$$

T is Fresnel transmittance of the boundary between two media with dielectric permittivities $\varepsilon_1 = \varepsilon_0$ (air) and $\varepsilon_2 = \varepsilon_{r2}\varepsilon_0$ (ε_{r2} is relative dielectric permittivity); $\gamma_j^2 = k_j^2 - 4\pi^2\nu^2$; $k_j = \omega^2 \varepsilon_j \mu_0 + i\omega\mu_0\sigma_j$, $j = 1,2$; ε_2, σ_2 are electrodynamical parameters characterising medium where cylindrical dielectric objects under investigation are embedded; ε_2 is dielectric permittivity; σ_2 is conductivity. Function $c_2(\nu)$ may be written in the integral form

$$c_2(\nu) = \iint_S K(x', y') \exp\left[-2\pi i (\alpha x' + \beta y') dx', dy'\right] \qquad (7)$$

where

$$\alpha = \nu - \frac{\omega}{c}\frac{1}{2\pi} sin\,\theta_1 \qquad (8)$$

$$-2\pi\beta = \sqrt{\left[\left(\frac{\omega}{c}\right)^2 \varepsilon_{r2} - 4\pi^2\nu^2\right] + i\frac{\omega}{c}120\pi\sigma_2} + \frac{\omega}{c}\sqrt{\left(\varepsilon_{r2} - sin^2\,\theta_1\right) + i\frac{c}{\omega}120\pi\sigma_2} \qquad (9)$$

θ_1 is an angle of incidence; symbol S denotes that integration is over the cross section S of object under investigation; function $K\left(x', y'\right)$ represents normalised the polarisation current which is sought for.

Thus desired function $K\left(x', y'\right)$ is found by means of inverse Fourier transformation and by function $\hat{\psi}\left(\nu(\alpha,\beta), y_1\right)$.

4. Proposed Tomography System

The setup described below is intended for reconstruction of a radiotomography images of weakly scattered objects. The functional scheme of the setup operating in frequency range of 4 ÷ 12 GHz is shown in Fig.2. The setup consist of: network analyzer; mechanical scanner; antenna system; personal computer and specialise software.

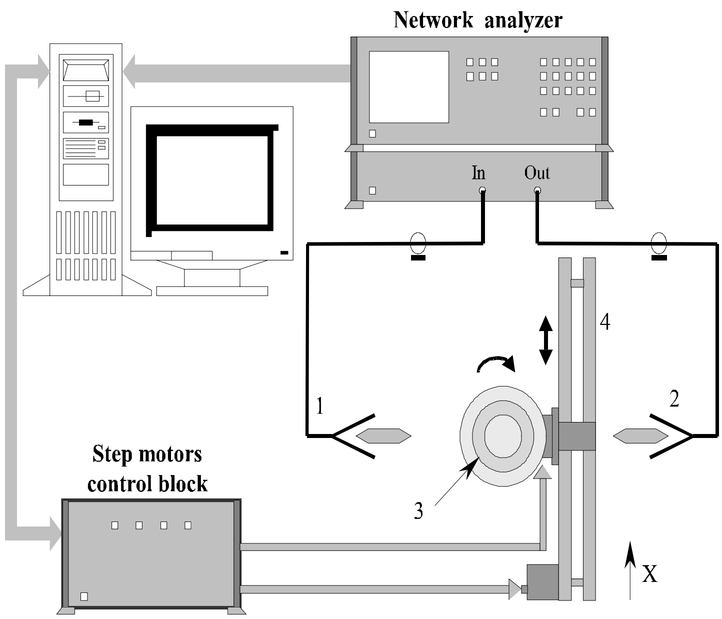

Fig. 2. Functional scheme of experimental setup.
(1 – receiving antenna, 2 – transmitting antenna, 3 – cylindrical object, 4 – scanner)

Scanner allows to move an object in linear direction with field of scanning in 2 m and to rotate an object on any angle in range 0÷360^0. Movement of scanner is completely controlled from the computer by the *step motor control block*. In our setup we used antennas of surface waves [5]. The antenna system consists of transmitting and receiving antennas, which have equal construction. Each antenna includes metallic rectangular waveguide and dielectric plate partially inserted in waveguide. Dielectric plate operates as longitudinal irradiator and longitudinal receiver respectively. Application software include equipment drivers, main program and program of image reconstruction from row experimental data. Main program controls equipment of the setup and all software is run under Windows 95/98.

In the experiment was used data about forward-scattered fields at frequency 7.5 GHz. The investigation was carried out with weakly-scattered dielectric in air. The field data were collected on direct line on distence 0.3 m with the space step $\Delta X \cong 0.005m$. The rotation axis of the target was placed on the center line between two antennas separated on distance 0.3 m. It the experiment dielectric objects with size of cross-section $D \cong 1 \div 3\lambda_0 (\lambda_0 \cong 0.04m)$ and highest $H \cong 3\lambda_0$ was investigated. Dielectric objects are made from materiel having relative dielectric permittivity 1.1÷2 (paper), which is close to one of surrounding medium. The images are obtained using first order diffraction tomography approach for weakly scattering objects having a simple structure. The imaging calculation method have been described in [4].

In fig.4 one can see experimentally obtained at 7.5GHz the cross-section image of paper cylinder. Shape of cross-section is formed by a compression of original circle cylinder with hole and by addition to one new circle cylinders.

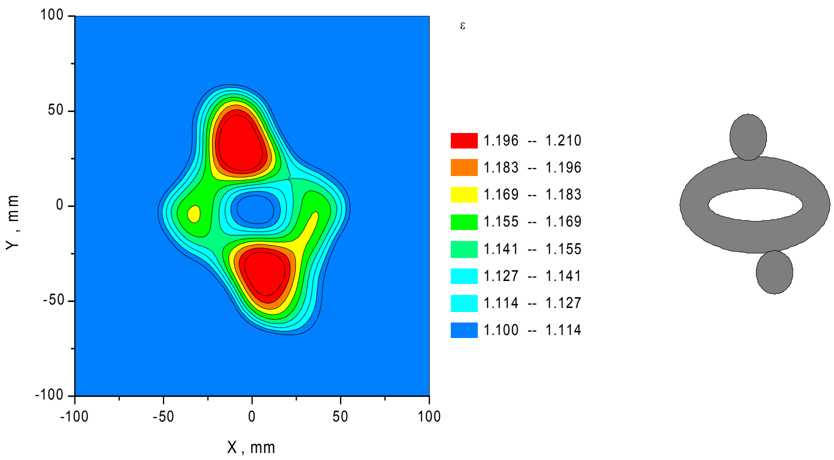

Fig.3.The reconstructed cross-section image (on the left) and original cross-section (on the right).

5. Development of Tomographic Methods in MM Wave Range

The setup schemes developed are shown in Fig.4, 5. One of them works at the frequency $f \cong 99$ GHz and it is assembled on base of waveguide components (Fig.4). Another one has operating frequency band $\Delta f \cong 125 \div 145$ GHz and was made out with using quasi-optical technique (Fig.5). The setups work on analogous principle. Fig.6 and Fig.7 show images $(\varepsilon(x, y) - 1)$ of the object cross-sections under experimental investigation by using quasi-optical setup ($f \cong 99$ GHz). Similar pictures are obtained with setup operating on the frequency 136.5 GHz.

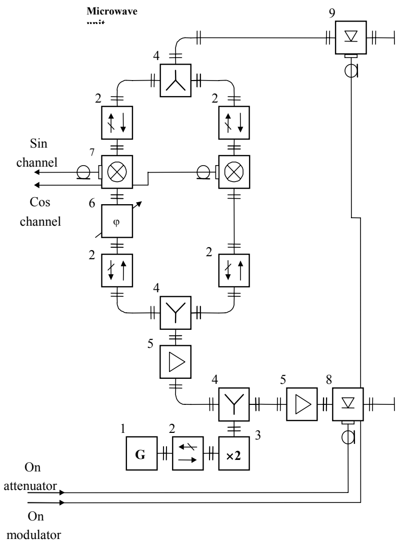

Fig.4. Functional scheme of 99 GHz unit
(1 - oscillator 49GHz; 2 - ferrite isolators; 3 - frequency doubler; 4 - 3dB splitters; 5- power amplifiers; 6- phase shifter; 7 - balanced mixers; 8 - p-i-n attenuator; 9 - p-i-n modulator).

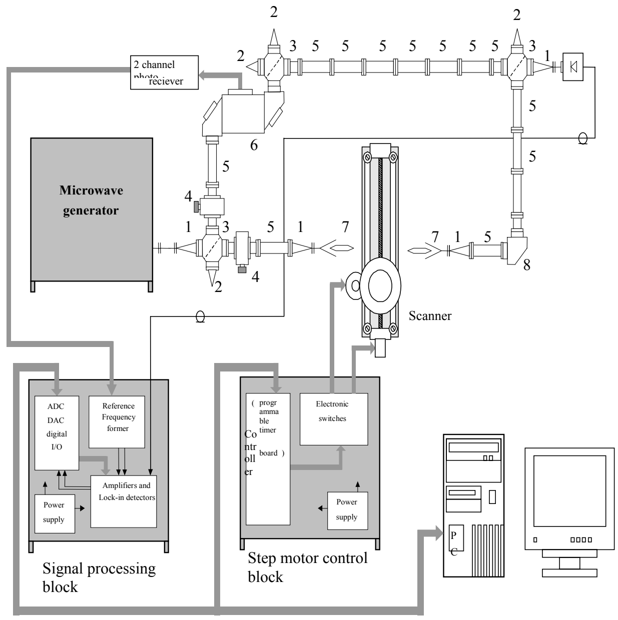

Fig.5. Functional scheme of 2 mm tomograph setup
(1 - waveguide to quasi-optical beam wave guide transformer; 2 - matched load; 3 - beam splitter; 4 - attenuator; 5 - quasioptical beam waveguides, 6 - frequency shifter; 7 - dielectric antennas; 8 - 90^0 degree turn; 9 - microwave detector).

Objects were made from plastic foam and had characteristic dimensions. $A \leq 20\lambda$. The reconstruction algorithm is based on the first-order diffraction tomography formulae.

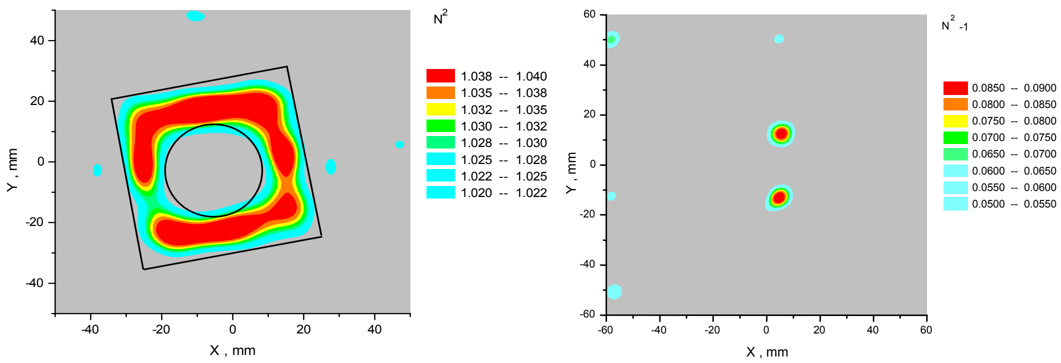

Fig.7

6. Subsurface Tomography Setup

The setup described below is intended for reconstruction of a radio tomography images of various buried objects in frequency range of 1.25÷5*GHz*. The functional scheme of the setup is shown in Fig.8.

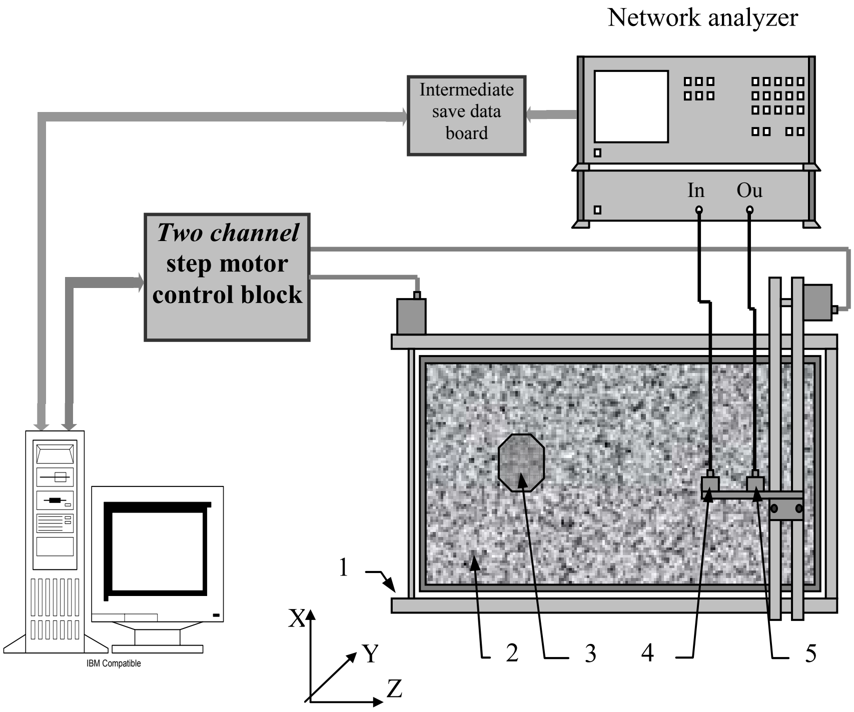

Fig.8. Schematic view of experimental setup.
(1 – XY scanner; 2 – medium; 3 – target; 4 – receiving antenna; 5 – transmitting antenna)

The 2-D scanner with area of $1.5\times2m^2$ consists of a mechanical part and a step motor control unit with two independent channels. Channels are intended for shaping current pulses in windings of step motor. Number of steps (or distance) and movement direction are controlled by the microcontroller based board in PC and by a special software. The scheme of antennas system is shown in Fig.9. In our opinion, within the range of antennas the pivot dielectric antennas could be happy choice for a practical tomography. And this is primarily due to the fact that they have the lowest aperture in the Fresnel zone, in comparison with other antennas. And the second, what is very important for the tomography, that the receiving and radiating antennas could be brought closer to each other to the distance much lower than that of the operating wave-length under isolation being preserved at minus 40dB.

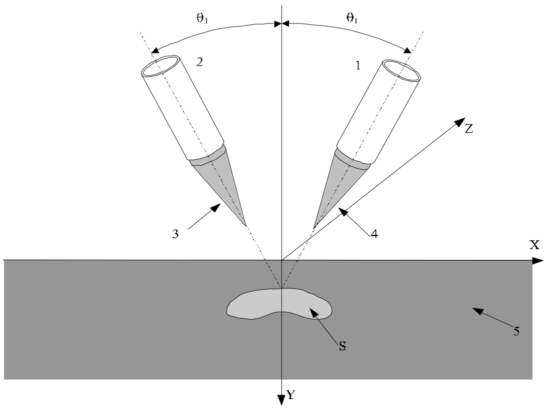

Fig.9 The scheme of the antenna system.

The principle of the radiation and reception antennas assumes the wave-guide-to coaxial adaptor, where the diameter of the adaptor to the round cross-section is 64mm, and also the fluoro-plastic cones with the total length of 350mm. An operating frequency range is 2.5-5.0 GHz. The microwave losses for a couple of antennas accounted approximately to –10dB under the non-uniformity for amplitude-frequency characteristic –2dB, the VSVR being 2.0.

The following objects are chosen to show tomography testing:1–a metal disk– the object, which has absolute microwave reflection and allows to get reference tomography images; 2 – a foam plastic brick with the dielectric properties similar to the sand; 3 – a plastic parallelepiped object with the dielectric permittivity similar to the sand. The objects were buried in sand on different depths. The scanning has been realised on the field of 30÷30 cm^2 with the step of 1 and 2 cm for both directions. The tomography testing were carried out in frequency range of 2.5÷5.0 GHz.

The Figures 13÷15 show the most specific tomography images ($|K|$- induced current) made for the subsurface objects. For finding correspondents between real dimension of the object and its tomography image we use "–3dB" level to the maximum of the amplitude of induced current. The Figure 10 shows the image of a metal disk with a diameter of 8.0 cm, buried into the sand at the depth of 20.0 cm. The image was obtained with the step of 1.0 cm. A specific feature of the tomography image for the metal object is a big value of $B = |K|_{max} / |K|_{min} \approx 10$. This value was used as reference level for the testing of the subsequent pictures. The fig.11 show the same disk but the step of scanning was 2.0 cm. A comparative analysis of these pictures shows the following. The dimensions of the object, got by above-mentioned criterion, at fig.10 and 11 are adequate to the physical ones with accuracy about 10%. The dimension of the image increased on 20% along X axis. This is related to spreading of near-field antennas field that is explained by impossibility to place antennas near then λ/4. The isometric image 12 shows the distribution of electromagnetic field in the sand from back side of the disk.

Fig.13 and 14 show a tomography image of a foam-plastic brick with dimensions of 8.0×4.0×1.0 cm which is buried into the depth of 7.0 cm. For fig.13 the scanning step was 1 cm and for fig.14 it was 2 cm. At fig.15 the plastic two-dimensional object (the dimensions are 13.0×8.0×4.5cm) is presented. The image of the object consists of two parts: hight and low value of B. Last one gives the part of the object completely filled with sand. According to the above criterion, the dimensions of all of objects coincide with its physical dimensions with the accuracy of 10%.

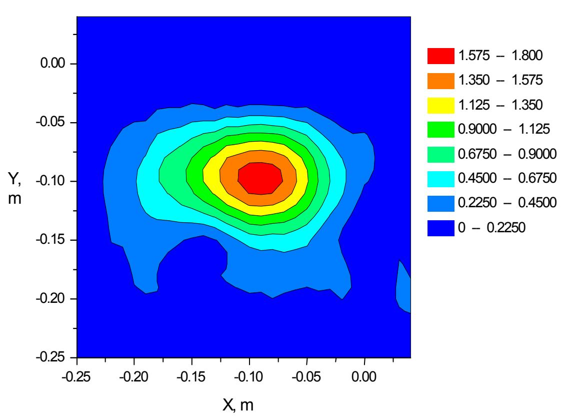

Fig. 10

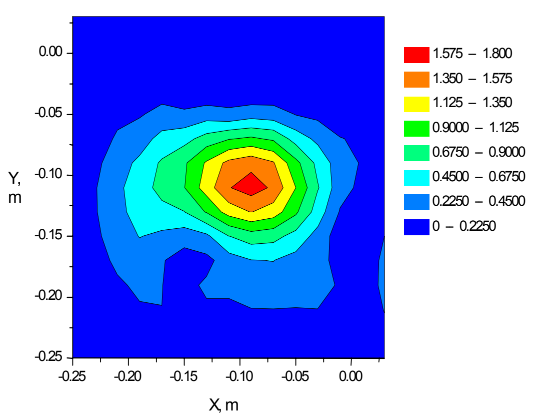

Fig. 11

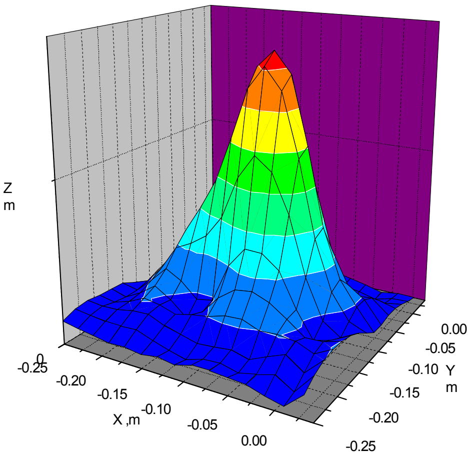

Fig. 12

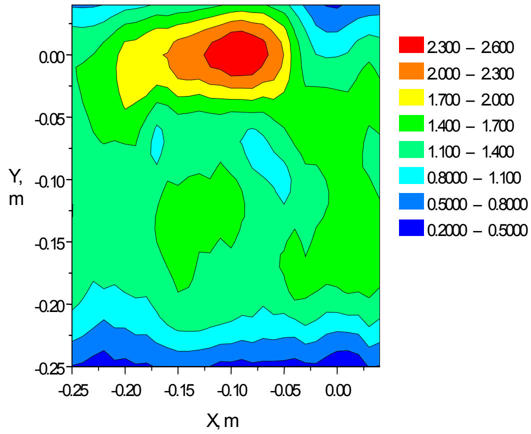

Fig. 13

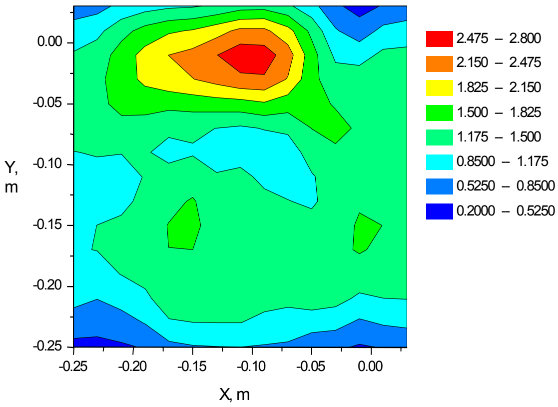

Fig. 14

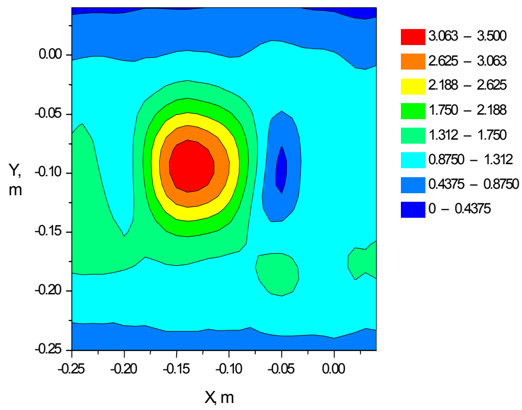

Fig. 15

7. Conclusion

Thus the carried out experimental investigation of developed tomographic systems showed that on their basis the microwave and millimeter wavelengths band tomographs for images of cross-sections of volumetric opaque to optical beams dielectric objects as well as surface images or subsurface structures may be created. The images are obtained using methods of first- order diffraction tomography for weakly scattering objects having a simple structure. But even the first approximation for the scattered field and information obtained by measurements of its phase and amplitude allow to study comparatively small objects (the object diameter is $D \cong 9\lambda$; dimension of inhomogeneity is $d \cong 4\lambda$; $\lambda \cong 3$ mm and $D \cong 2\lambda$; dimension of inhomogeneity is $d \cong \lambda$; $\lambda \cong 6$ cm) at refractive index of the material is $n \cong 1.03 \div 1.1$. In the process, a high quality of image of the object investigation is obtained.

The tomographic subsurface testing carried out with three different (according to their dielectric profile) objects has proved the following:

The microwave tomography makes it possible to get images of subsurface objects within the frequency range of 2.5÷5.0 GHz. The ratio amplitude of induced current for the image of a metal object could be a criterion for evaluation of reliability of the image obtained. The criterion for determination of dimensional object is the level–3dB of induced current. The accuracy for the detection of two-dimensional object must not be lower than 10%. The microwave technology makes it possible to detect subsurface objects both for metal and dielectric materials.

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