Microwave Tomography: Theoretical and Experimental Investigation of the Iteration Reconstruction Algorithm

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***Abstract*—Results of experiments on the two-dimensional (2-D) quasi-real-time microwave tomographic system have been reported [1]. Various reconstruction possibilities of this system have been demonstrated on phantoms and canine hearts. The early utilized Rytov approximation is appropriate for low-contrast inverse problems. A new iterative reconstruction algorithm is proposed in this paper. The iterations converge to an accurate solution of the scalar Helmholtz-equation inverse problem in the case of higher contrasts. The goal of the reported study is an experimental and theoretical investigation of the proposed iteration algorithm. The influence on the quality of the reconstructed images and on the spatial resolution of such factors as the number of receivers, the accuracy of the scattered field measurements, and the dielectric contrast have been investigated.**

***Index Terms*— Image reconstruction, inverse problems, iterative methods, microwave image tomography,**

I. Introduction

MICROWAVE tomography is a new technology which has enormous potential advantages in medicine [2], [3]. The difficulties and advantages of medical applications of microwave tomographic imaging have been discussed by the present authors in [1]. It is well known that data obtained in diffraction tomography (DT) are difficult to deal with. A highly complicated process of the diffraction of electromagnetic (EM) waves on the internal structures of the object under investigation makes it impossible to use well-developed methods of X-ray tomography [4]. Two main approaches are discussed in the current literature. One of them is the linearization of the problem through the use of the Born or Rytov approximations [2]–[4], while the other is a direct minimization of a functional derived from the wave equation [5]–[9]. Both approaches are of limited usage. The former is effective from the calculational point. At the same time, it is restricted to relatively small gradients of the permittivity of the object. This is especially true in the case of the Born approximation. The latter, considered to have no restrictions on the gradients, becomes extremely expensive with the growth of the number of points where the permittivity have to be determined. This makes it difficult to be applied to any object having a complicated internal structure.

An iterative algorithm of the inverse problem solution utilizing the Rytov approximation is proposed in this paper. The Rytov reconstruction technique is implemented to obtain an approximation to the distribution of the object permittivity. The scattered EM field is calculated with these permittivities taken as the input data for the direct problem solution. After that, the difference between the calculated scattered field and the measured one is used to calculate a correction to the object permittivity. When a repetition of these calculational steps shows a convergence (if any) it means that a precise solution of the inverse problem is achieved. Our investigations proved that this algorithm does converge for the objects with a moderate gradient of permittivity when the first Rytov approximation gives a reasonable estimation. A very similar iteration technique for the Born approximation was discussed earlier in [10].

The most time-consuming part of this algorithm is the direct problem solution. Later in this paper, we discuss a simple direct problem solver that proved to be effective for the objects with a moderate gradient of permittivity.

For the standard Rytov reconstruction technique, one should use a parallel-beam transmission tomographic configuration in which a plane wave propagates through the object and the transmitter field is measured on a straight line. None of these points are true in the case of our tomograph with a cylindrical chamber and finite aperture transmitters. To solve this problem, we have designed mathematical algorithms that synthesize a plane wave through the use of transmitters located equidistantly on the perimeter of the cylindrical working chamber transmitters, and transfer scattered-field data from cylindrically located receivers to a straight line behind the object.

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It was concluded in our previous paper [1], that the current number of receivers (32) was not sufficient and should be increased for accurate measurements of high oscillations of the EM field caused by the interference of the incident and scattered waves. Other factors influenced on the image quality are an accuracy of the scattered field measurements and the dielectric contrast. An investigation of the influence of the above factors on the quality of the reconstructed images is a goal of this paper's investigation.

II. Experimental Setup

A two-dimensional (2-D) prototype microwave tomographic system was constructed. A detailed system description has been presented elsewhere [1]. The working frequency of this system was 2450 MHz. It was composed of 64 antennas (32 emitters and 32 receivers) located on the perimeter of a cylindrical working chamber with an internal diameter of 36 cm.

The reproducibility of experimental investigations requires an utilization of special phantoms with known and repeatable dielectric properties and geometrical shape. The early utilized gel phantom [1] did not fill this requirement. Two asymmetrically enclosed cylindrical containers with thin plastic walls have been constructed. The container cylinders have diameters of 6.5 and 2.1 cm. The inner container was filled with a surrounding liquid with $\varepsilon = 77.8 + i10.2$. The outer one was filled with a liquid with $\varepsilon = 68 + i10$. An estimated accuracy of the dielectric properties measurements of this phantom was approximately 5%. The phantom was placed in the center of the microwave chamber.

The microwave chamber was filled with solutions of various permittivities. The permittivity of all solutions was measured by a dielectric probe and an HP8753C Network Analyzer.

III. The Iterative Algorithm of the Inverse Problem Solution

With the incident wave E_0, the Rytov approximation to the phase Φ of the transmitted field $E = E_0 \exp(\Phi)$ in the point $\mathbf{r}$ is given as a linear operator $\hat{A}$ over the cross section of the object [4] as follows:

$$\begin{aligned}\Phi(\mathbf{r}) &= \hat{A}(\varepsilon - \varepsilon_0)\\ &= \frac{ik_0^2}{4E_0(\mathbf{r})\varepsilon_0}\int E_0(\mathbf{r}')H_0^1(k_0|\mathbf{r}-\mathbf{r}'|)(\varepsilon(\mathbf{r}')-\varepsilon_0)\,d\mathbf{r}'\end{aligned} \tag{1}$$

where k_0 and ε_0 are the immersion liquid wavenumber and permittivity, $\varepsilon(bfr)$ is the permittivity distribution in the object, and H_0^1 is the zeroth-order Hankel function. If the incident wave is a plane wave and the transmitted field is measured on the straight line, the Fourier transform of (1) leads to the generalized projection-slice theorem of DT, which forms the basis for a number of effective treatments of the DT reconstruction problem [2], [4] in the linear approximation. These methods include the filtered backpropagation algorithm and the Fourier inversion method. Both have been widely discussed in the literature and their description can be found in the above references. In our investigation we used the latter.

If we take into account the terms neglected in the Rytov approximation, the relation between the phase Φ of the transmitted field and dielectric permittivity ε of the object becomes the nonlinear equation

$$F(\varepsilon) = \Phi. \tag{2}$$

This equation can be identically transformed to

$$\hat{A}\varepsilon = \hat{A}\varepsilon + \Phi - F(\varepsilon). \tag{3}$$

As long as the linear operator $\hat{A}$ is not a very bad approximation to the nonlinear function F, the following iterative method of successive substitutions should converge:

$$\begin{aligned}\varepsilon^1 &= \varepsilon_0 + \hat{A}^{-1}\Phi\\ \varepsilon^{n+1} &= \varepsilon^n + \hat{A}^{-1}(\Phi - F(\varepsilon^n)).\end{aligned} \tag{4}$$

Every next iteration involves a direct problem solution with the previously determined permittivity distribution (evaluation of $F(\varepsilon^n)$) and a Rytov inversion denoted in (4) as $\hat{A}^{-1}$. As the former step is much more time consuming, we will discuss our approach to it in some detail. The direct inversion of the Lipmann–Schwinger integral equation is the most straightforward and very frequently used way to solve the direct problem. If the mesh used to cover the object region has N nodes, the number of operations is proportional to N^3 and the integral equation inversion quickly become unusable with the growth of N. Thus we start from the Helmholtz equation for the scattered field E_s:

$$\nabla^2 E_s + k^2 E_s = \left(k_0^2 - k^2\right)E_0. \tag{5}$$

The boundary condition for this equation is the absence of the incoming scattered wave outside the object (7). For relatively small values of the permittivity contrast between the object and the immersion liquid $|1 - \varepsilon/\varepsilon_0| < 1$, a very simple, but effective and robust, iterative algorithm can be suggested:

$$\nabla^2 E_s^{l+1} + \bar{k}^2 E_s^{l+1} = (\bar{k}^2 - k^2)E_s^l + \left(k_0^2 - k^2\right)E_0. \tag{6}$$

If $\bar{k} = k_0$, these iterations are identical to the Liouville–Neumann series solution. To increase the efficiency of iterations, this value should be taken to minimize the norm of $\bar{k}^2 - k^2$. To solve (6), we are going to use the Fourier transform $\tilde{E}_s^m(r) = \int \exp(-im\varphi)E_s(r,\varphi)\,d\varphi$ in the cylindrical coordinate system, so $\bar{k}(r)$ can be a function of r. In our calculations, we place it somewhere in the middle between maximal and minimal values of the k for a given r. The boundary condition is formulated on the circle of a radius R, which lies entirely beyond the boundaries of the object

$$\frac{\tilde{E}_s^m(R)'}{\tilde{E}_s^m(R)} = \frac{H_m^1(k_0R)'}{H_m^1(k_0R)} \tag{7}$$

where $H_m^1(k_0R)$ is the Hankel function of order m. Analyzing the number of operations taken by the Fourier transform

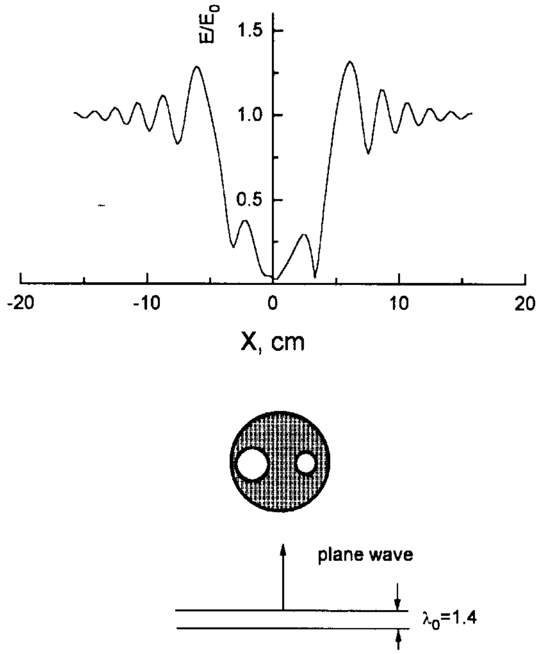

Fig. 1. Diffraction of a plane wave on the model object with the permittivity of the myocardium tissue surrounded by the water.

and subsequent solution of the differential equations, we can conclude that number of operations for every iteration step, (7) is roughly proportional to the number of mesh nodes N. A typical number of iterations in our direct problem calculations was about 15.

An example of the direct problem solution is presented in Fig. 1 where a plane wave with $\nu = 2450$ MHz propagates through the water ($\varepsilon_0 = 77.8 + i10.2$) and irradiates an object that has dielectric properties close to the myocardial tissue ($\varepsilon = 54 + i15.2$). The object is a cylinder of a diameter 8 cm and has two holes of radii 1.5 cm and 1 cm filled with the water. The EM field is taken on a straight line separated 5 cm from the center of the object.

IV. Plane Wave Synthesizing

To adopt the above method to our experimental system, we had to take two steps: synthesize a transmitted plane wave by properly phasing and weighing the waves transmitted at each transmitter location on the tomograph circle of radius R and, from the experimental data on the tomograph circle, calculate the scattered wave on a straight line parallel to the axis and located behind the object.

Let us consider the decomposition of the plane wave on the circular waves in the cylindrical coordinates

$$e^{ik_0 r \cos\varphi} = \sum_{n=-\infty}^{\infty} i^n e^{in\varphi} J_n(k_0 r) \tag{8}$$

where J_n is the Bessel functions. The field from a transmitter located in the point (R, φ_j) can be decomposed as well:

$$E_j = \sum_{n=-\infty}^{\infty} b(k_0 R, n) e^{in(\varphi - \varphi_j)} J_n(k_0 r) \tag{9}$$

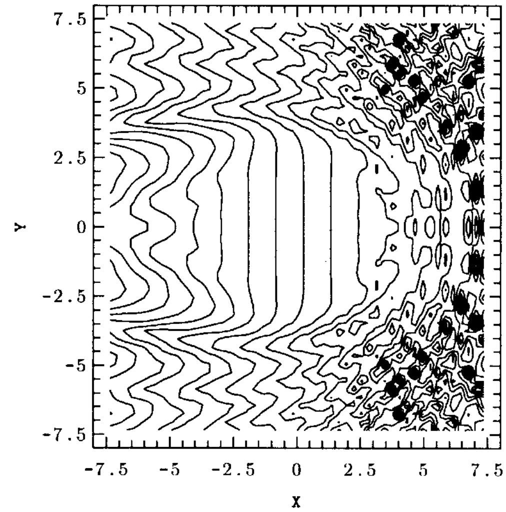

Fig. 2. Generation of plane wave by 32 transmitters.

where the coefficients $b(k_0 R, n)$ depend on the characteristics of the transmitter and for a transmitter of the width W they are equal:

$$b(k_0 R, n) = H_n^1(k_0 R) \frac{\sin \frac{\pi W}{R}}{\frac{\pi W}{R}}. \tag{10}$$

To synthesize a plane wave N, transmitters must irradiate with amplitudes C_j, which satisfy conditions

$$\sum_{j=0}^{N-1} C_j e^{-in\varphi_j} = \frac{i^n}{b(k_0 R, n)}. \tag{11}$$

It is evident that with a finite number of transmitters we can satisfy a finite number of equations (11), so that the plane wave will be synthesized only in a restricted area of the tomograph. If transmitters are uniformly spaced along the circle these equations can be solved easily to obtain

$$C_j = \frac{1}{N} \sum_{n=-N/2+1}^{N/2} e^{in\varphi_j} \frac{i^n}{b(k_0 R, n)}. \tag{12}$$

Isolines of the amplitude of the synthesized wave for $N = 32$ are shown in Fig. 2. We can conclude that there is an area of diameter about 10 cm from where the plane wave can be reasonably synthesized.

If the scattered field is measured on a circle of the radius R it can be freely calculated at any point (r, φ), provided that the circle of the radius r lies entirely outside the boundaries of the object. To do so, one can use the proportionality of the Fourier transforms E_s^m in a homogeneous medium to the Hankel function $H_m^1(k_0 R)$. In the following equations, α is introduced to compensate the amplification of experimental errors and should be determined empirically:

$$E_s^m(r) = E_s^m(R) \frac{\xi^*}{|\xi|^2 + \alpha m^2}$$
$$\xi = \frac{H_m^1(k_0 R)}{H_m^1(k_0 r)}. \tag{13}$$

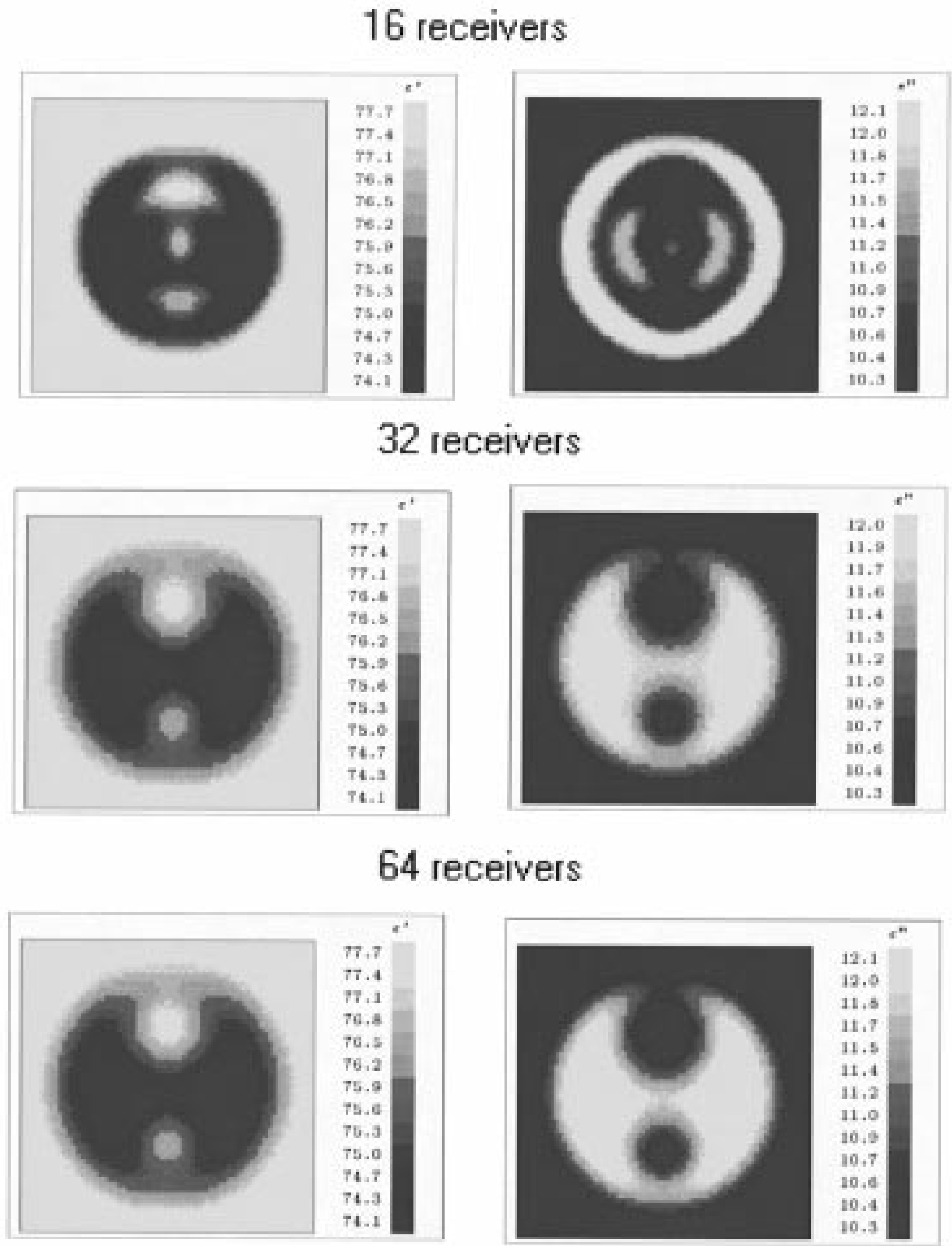

Fig. 3. Comparison of the object reconstruction with different numbers of receivers.

V. Results

A series of model calculations were undertaken to investigate the possibilities and limitations of the above algorithm. For this case, a mathematical model of the object was taken which is composed of a cylinder of a diameter of 8 cm with two holes of diameters 3 and 2 cm. The immersion liquid and the medium in the holes were water with the permittivity $\varepsilon_0 = 77.8 + i10.2$ at the frequency 2450 MHz. Three values of the object permittivity $\varepsilon = 73.9 + i10.2$, $\varepsilon = 70 + i11.2$, and $\varepsilon = 62.2 + i12.2$ (will be referred to later as the permittivity contrast of 5%, 10%, and 20%, subsequently) were considered. To simulate the experimental situation, the direct problems were solved for 32 transmitters distributed evenly along a circle of radius 16.5 cm and the values of the scattered field were obtained in the locations of M receivers placed along the backward half of a circle of a radius of 16 cm. These values were used in the above algorithm instead of the experimentally measured fields. The results obtained after ten iterations (4) for the case of the 5% contrast for M equal to 16, 32, and 64 are presented in Fig. 3. It is clearly seen that in our model, 16 receivers for every direction of irradiation are obviously insufficient, while 64 receivers are only slightly better than 32.

In Figs. 4–6, a comparison is made between reconstructions of objects with different permittivity contrasts for the case of $M = 32$. The result of the Rytov approximation, the tenth iteration result, and the mathematical model of the object itself are presented. For two lower values of contrast the iteration process managed to obtain an exact solution while for the

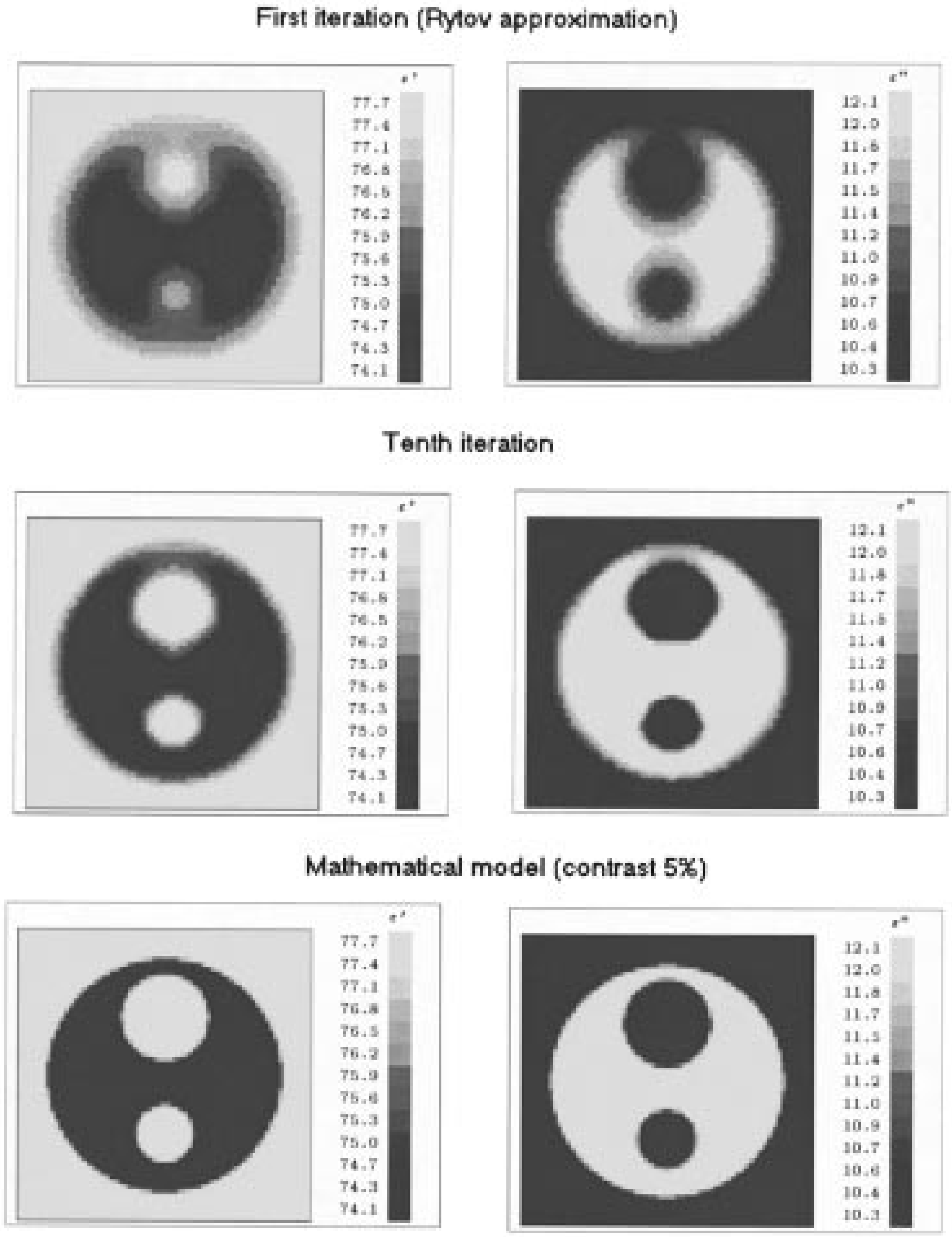

Fig. 4. The reconstruction of the 5% contrast mathematical model.

highest value of contrast it did not show sufficient convergence and the final result was poor.

To realize the sensitivity of the algorithm to possible experimental errors, random noise of a different amplitudes was added to the scattered field before the reconstruction. We were able to obtain images if the error was as big as 5%. But in this case, the images were deformed significantly and, hence, this value could be considered as the possible upper limit of the experimental error in reconstruction of the above objects. On the other hand, we estimated that to obtain an accurate image reconstruction it is necessary to have experimental errors not higher than 0.1%–1.0%.

The results of the experiments on the container phantom (for an explanation, see Section II) is shown in Fig. 7 where the reconstructed real part of dielectric permittivity is presented. Five iteration have been made in the reconstruction procedure. The inner container was filled with surrounding water with $\varepsilon = 77.8 + i10.2$. A good image reconstructed have been achieved. The inner hole have been exactly spatially and contrastively reconstructed. An additional surprise from this experiment is that the achieved spatial resolution is even better than expected (near $\lambda/2$). The reconstructed image presented in Fig. 7 is estimated as ideal in our experimental case.

VI. Discussion

It was concluded in our previous report [1] that the number of receivers in our tomographic system is not sufficient. The

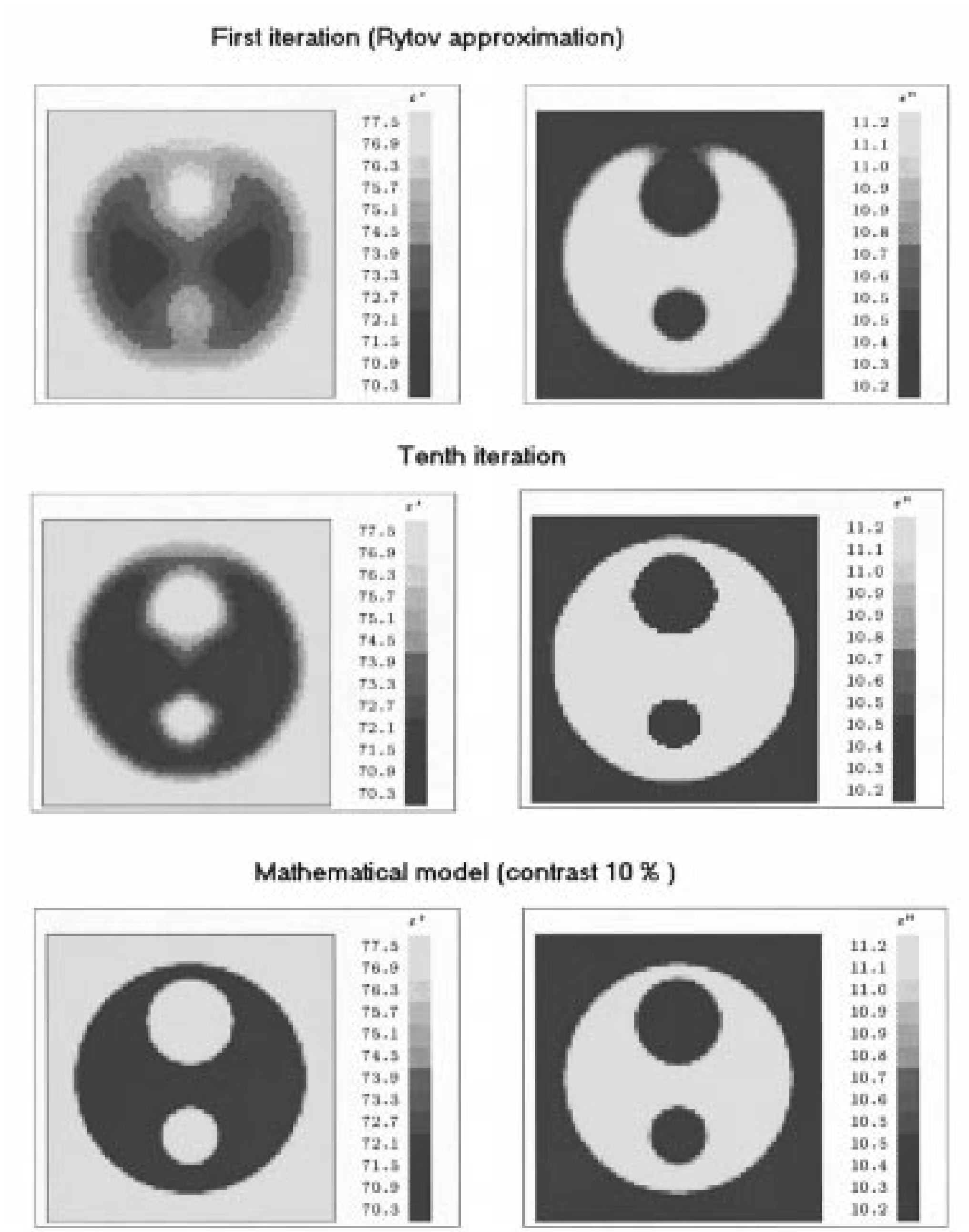

Fig. 5. The reconstruction of the 10% contrast mathematical model.

model calculations have been conducted for 32 transmitters located equidistantly on the perimeter of the tomographic chamber with radius 16.5 cm. It is clearly seen in Fig. 3 that 16 receivers for every direction of irradiation are obviously insufficient while 64 receivers are only slightly better than 32. Those calculations demonstrate an improvement of the quality of the reconstructed as a consequence of an increase of the receivers number. On the other hand, a simple expression of such a type "image quality—number of receivers" has not been found, which is seen from the comparison of the images for 32 and 64 receivers. The geometry of a tomographic chamber, an emitter and a receiver radiation patterns, an antennae object matching, an expected spatial and contrast resolution, etc. have to be taken into account.

In microwave tomography, the tissues are differentiated on the basis of various permittivities. On one hand, it is very fortunate that various tissues have a high contrast of the dielectric constant, so various tissues can be easily differentiated. For example, for a frequency of 2450 MHz, ε has a value of about 5.5 for fat or bone and about 50 for tissues with high water content, such as myocardium. On the other hand, the high contrast in tissues dielectric properties creates a problem for the mathematical reconstruction. It is well known that the Rytov approximation is appropriate in low-contrast cases. We proposed an iteration process for higher contrast cases. An iteration procedure used the Rytov approximation as the first step. As can be seen from Figs. 4–6, for two lower values of the contrast the iteration process managed to obtain an

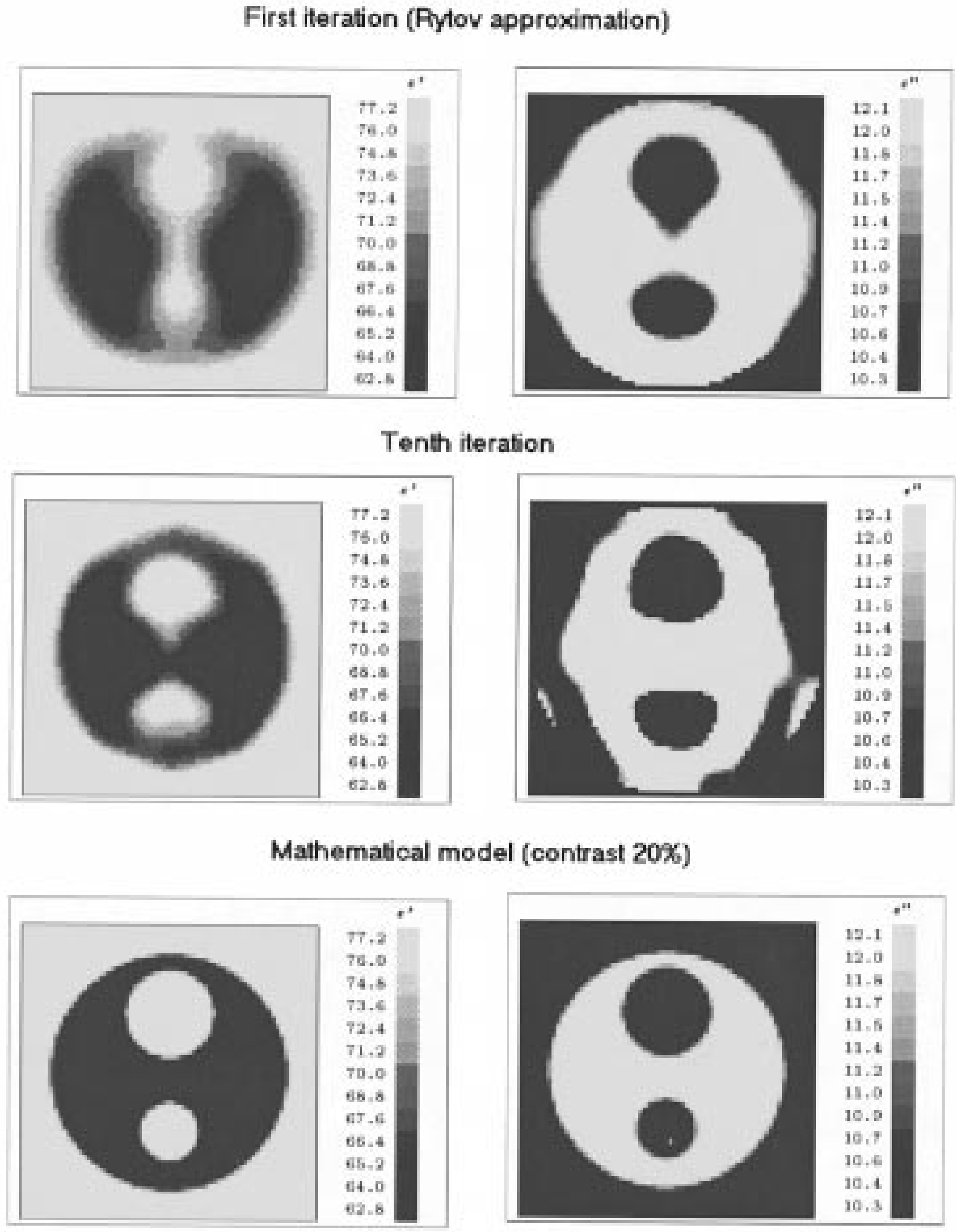

Fig. 6. The reconstruction of the 20% contrast mathematical model.

exact solution, while for the highest value of the contrast it did not show sufficient convergence and the final result was poor.

As was mentioned above, the estimations of an experimental errors for the qualitative imaging are approximately 5% and for the accurate image reconstruction are approximately 0.1%–1.0%. A second request for experimental setup is not easy to perform, especially for a whole body real-time systems. We will describe our technical solutions for such a system in the future.

The reconstructed image presented in Fig. 7 for the asymmetrical cylinder containers is estimated as almost ideal for our experimental situation. The inner hole has been reconstructed exactly spatially and contrastively.

VII. Conclusion

The proposed mathematical reconstruction algorithm based on the iteration procedure managed to obtain an exact solution of mathematical models and a real phantom in the case of about 10%–15% values of the dielectric contrast. The only qualitative image reconstruction was achieved in the case of a higher dielectric contrast.

The proposed inverse problem solution algorithm requires a plane wave object irradiation. Even in the case of a small number of transmitters (32), the proposed algorithm allowed us to create an area of the plane waves in the center of the tomographic chamber that is sufficient for investigating of objects with a diameter as big as 10 cm. An investigation of

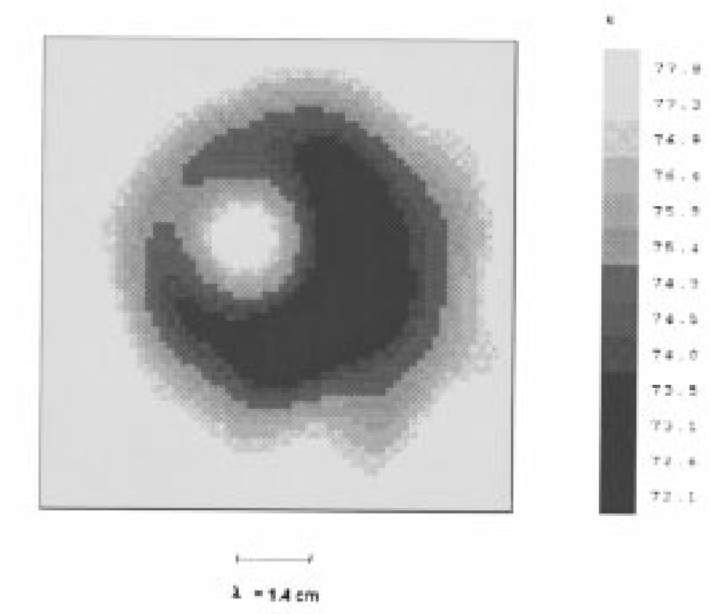

Fig. 7. Reconstruction after five iteration of the real part of the permittivity of the liquid phantom (two asymmetrically in closed container) place in water.

bigger objects will demand either increase of the transmitters number or abandonment of the parallel beam configuration or both. The improvement of the quality of the reconstructed images produced by an increase of the receivers number suggests that this number must be at least twice as much.

A request for experimental errors for images reconstruction is about 5% for the "qualitative" imaging and about 0.1%–1.0% for the accurate image reconstruction.

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