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Application of Two-Dimensional Discrete Dipole Approximation in Simulating Electric Field of a Microwave Breast Imaging System

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Abstract

The two-dimensional electric field distribution of the microwave imaging system is numerically simulated for a simplified breast tumour model. The proposed two-dimensional discrete dipole approximation (DDA) has the potential to improve computational speed compared to other numerical methods while retaining comparable accuracy. We have modeled the field distributions in COMSOL Multiphysics as baseline results to benchmark the DDA simulations. We have also investigated the adequate sampling size and the effect of inclusion size and property contrast on solution accuracy. In this way, we can utilize the 2D DDA as an alternative, fast and reliable forward solver for microwave tomography. From a mathematical perspective, the derivation of the 2D DDA and its application to microwave imaging is new and not previously implemented. The simulation results and the measurements show that the 2D DDA is a well-grounded forward solver for the specified microwave breast imaging system.

Keywords

Computational electromagnetics; forward solvers; discrete dipole approximation; tomography; microwave imaging

I. INTRODUCTION

Many people around the world suffer from a range of cancers which has lead numerous research groups to investigate various diagnostic approaches. Studies on cancer frequency from the Word Cancer Research Fund International (WCRF) report that in 2012, 14.1 million people suffered from different types of cancer and the expectation is that it will grow to 24 million cases by 2035 [1]. Breast cancer is ranked as the most common cancer among

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women with its contribution being 25 percent of all cancers [1]. Although developed countries such as Belgium, United States of America and Australia are among the top 20 countries with the highest rates of breast cancer, available data show notable levels of cancer incidence in less developed and developing countries. Recent research at institutes such as Cancer Research Centre of the United Kingdom [2] indicates that expanded monitoring programs improve the patient's odds of beating cancer through treatments. Since both early diagnosis and effective therapies are valuable in saving lives [2], many groups around the world are exploring possible approaches for early stage diagnosis. In addition to conventional imaging systems such as X-ray mammography, ultrasound and magnetic resonance imaging (MRI), microwave tomography has been proposed by numerous groups worldwide as one of several new alternative screening methods for cancer detection [3]–[10]. Previous investigations on contrast in dielectric properties between normal (both adipose and fibroglandular) and malignant breast tissues at microwave frequencies demonstrated meaningful contrast [11]–[18], and it is a crucial motivation for developing microwave tomography for breast cancer detection.

Microwave tomography (MT) is well positioned for meeting the desired goals of real world applications. It means it should be accurate, economical, user-friendly, compact, time-saving and portable. MT is an essential innovation in the quest to develop such system. While these systems have been studied extensively, the majority of them are plagued by requiring excessive computational resources and a high numbers of antennas. Our platform is unique in that it is already simple, does not require a priori information - like many others, utilizes only 16 antennas and has been deployed extensively for clinical exams. One of the key promises of microwave imaging is that the technology can ultimately be delivered very inexpensively when produced in large quantities.

Along this line, we are also interested in developing a fast and reliable reconstruction algorithm which can ideally be run on a laptop computer. While microwave imaging techniques are typically broken into three categories: radar [19], tomography and holography [20], in this paper we focus only on the tomography case, since it is the only one of the three that requires extensive computation of the forward model. These computations are always the time-limiting process. Accuracy and time efficiency are required for both forward solvers and inverse algorithms for tissue imaging. In particular, the forward solution is typically the most significant time cost and requires substantial attention to reduce its impact. Microwave tomography research groups have used different numerical methods for the forward solvers including finite elements (FE) [21], finite-difference time-domain (FDTD) [22] and integral equations [23] along with a variety of reconstruction algorithms including the distorted Born approximation, contrast source inversion and Gauss-Newton approaches [24]–[26]. Among the range of computational forward solution methods currently used in 3D microwave imaging, the discrete dipole approximation appears to be a promising technique for improving computational efficiency [27]. Grzegorzczuk et al. [27] previously demonstrated the 3D DDA in microwave tomography using clinical data from the Dartmouth microwave imaging system. One critical caveat is that DDA is known to work best in purely dielectric media. Our configuration effectively meets this criterion because of a synergistic combination of the lossy coupling bath and utilization of low profile monopole antennas which produces minimal perturbation to the field patterns.

In parallel to the many 3D simulations efforts, significant development has also been achieved for 2D approaches. 2D techniques have been applied successfully to phantom and animal experiments along with numerous clinical exams [3], [8], [28]. 2D microwave imaging has already been used widely because of its high quality images along with cost effective memory and CPU requirements. Applying DDA in 2D imaging may further diminish computational limitations in microwave tomography possibly to the level of near real-time. To the best of our knowledge, derivations of 2D DDA and its application in microwave tomography are unique.

We hypothesize that the principal reason for this is that the DDA's main advantage is for reduced computation time; primarily it produces the most substantial impact in research utilizing 3D forward simulations. For many 2D forward simulations, the need for speed enhancement is minor because the computation time is already short. However, in the context of performing hundreds of forward solutions associated with an iterative imaging algorithm, improved speed enhancement can still be meaningful. We propose to integrate the 2D DDA into our existing 2D reconstruction algorithm. For this study, we focus primarily on the derivation of the 2D DDA forward solver and assess its accuracy. The computational aspects for the 2D DDA are not discussed here but will be the main topic for a follow-on paper.

In this paper, we perform a comparison between a simplified 2D DDA forward model and a commercial finite element solver (COMSOL). We investigate field scattering contributions from simple inclusions with respect to their properties and sizes to assess the range of contrast where the DDA works appropriately. In Section II we report on the configuration of an imaging system and the numerical methods. Finally, in Section III we present computed 2D electric field distributions and error analyses for different parameter studies regarding scatterer size and dielectric property contrast along with a comparison of measured and computed fields.

II. FORWARD MODELLING: METHODS AND TECHNIQUES

For the microwave imaging system at Chalmers University of Technology, shown in Figure 1, an array of 16 monopole antennas moves vertically through seven measurement positions with all antennas functioning both as transmitters and receivers. Meaney et al. [8] and Rydholm et al. [29] have demonstrated the ability to recover high-quality images at different planes. This antenna array configuration is suitable for providing good imaging coverage of the patient breast. A schematic diagram for the 3D/2D forward model is presented in Figure 2. For the 2D scalar electric field (i.e., TM mode) of the imaging system, we only consider the forward solution case where a radiating antenna is located along a circle of diameter 15.2 cm. Since the monopole antenna in a plane acts similarly to an electric line source (ELS), the 2D field propagation for a system in the absence of inclusion can be computed as if it were a point source. For our modeling situation, we assume a complex and frequency dependent permittivity (1)

$$\epsilon(\omega) = \epsilon_r \epsilon_0 + \frac{j\sigma}{\omega}, \quad (1)$$

where ϵ_r , ϵ_0 , σ and ω represent the relative permittivity, free-space permittivity, conductivity and angular frequency, respectively. The background wave number squared is

$$k_b^2 = \omega^2 \mu_0 \epsilon_0 \epsilon_r + j\omega \mu_0 \sigma \quad (2)$$

where μ_0 is the magnetic free-space permeability.

A. Discrete Dipole Approximation (DDA)

The discrete dipole approximation, also known as the coupled-dipole method, is a numerical method based on volume integral equations [30]. Purcell and Pennypacker [31] introduced the DDA based on dividing a computational domain of volume V into N sub-volumes V_i . The total electric field in any sub-volume is related to the incident electric field ($E_{inc,i}$), plus a scattering contribution from all other dipoles, and is modelled with the susceptibility (χ_i) and dyadic Green's function ($\bar{\bar{G}}(R)$) at each sub-volume V_i . More theoretical aspects on the derivations of this method and a comprehensive review on recent developments for the 3D DDA are given in [30]–[33].

1) DDA and the Microwave Breast Imaging System: For the application of the DDA to our microwave imaging system, field propagation due to an antenna, as a source of incident electric field, is modeled utilizing an array of dipoles presented in either 2D or 3D geometry. We model the physical geometry of our imaging system with dipoles. Figure 3 presents a 2D geometry of a uniform grid with different dipole spacings accommodating different levels of resolution. As an antenna radiates a wave, the total electric field imposes a dipole moment at each dipole. This induces a dipole moment P_i caused by the electric field $E_{tot,i}$ for each dipole i and is given by

$$\bar{P}_i = \alpha_i \bar{E}_{tot}(\bar{r}_i) \quad (3)$$

Here the dipole polarizability α_i represents the strength in each dipole's response to the electric field. The total electric field at any dipole location r_i is the sum of the incident electric field due to a line source plus joint responses from the other $N - 1$ dipoles and is governed by [30].

$$\bar{E}_{tot}(\bar{r}_i) = \bar{E}_{inc}(\bar{r}_i) + \sum_{\substack{j=1 \\ j \neq i}}^N \bar{\bar{A}}_{ij} \bar{P}_j, \quad (4)$$

where $\vec{\cdot}$ and $\bar{\cdot}$ are vector and matrix notations, respectively. The $\bar{\bar{A}}_{ij}$ term from the Green's function for the 2D Helmholtz equation [34] shows interaction between two dipoles located at r_i and r_j and is written as

$$\bar{\bar{A}}_{ij} = \frac{-j}{4} H_0^{(2)}(k_b r_{ij}) \quad (5)$$

r_{ij} is the distance between nodes i and j , k_b is the wave number for the background medium, and $H_0^{(2)}$ is the zero-order Hankel function of the second kind. $\bar{E}_{inc}(\vec{r}_i)$ is the complete incident electric field distribution at location r_i caused by an electric line source (ELS). $\vec{P}_j$ represents the dipole moments [30]. From this formulation, we obtain the electric field by solving a linear system of equations. The polarizability at each dipole has previously been modeled for the three-dimensional case utilizing different coefficients with the most widely used one having been introduced by Draine and Goodman [35].

2) Two-Dimensional Discrete Dipole Approximation: In a similar fashion to the 3D case, we describe the 2D DDA via matrix equations comprised of N dipoles. We insert (3) into (4) to calculate the dipole moment vector P via

$$\bar{E}_{inc}(\vec{r}_i) = \left(\frac{1}{\alpha_i} - \sum_{\substack{j=1 \\ j \neq i}}^N \bar{\bar{A}}_{ij} \right) \vec{P}_j \quad (6)$$

In (6), $\left(\frac{1}{\alpha_i} \right)$ is the inverse of dipole polarizability and the interaction matrix $\bar{\bar{A}}$ is calculated from (5). Solving the system of equations in (6) for the vector $\vec{P}$ provides the scalar terms P_i . From this, we express the total electric field at r_i with the help of (4).

Throughout this paper, we employ the Clausius-Mossotti polarizability which relates the relative permittivity ϵ_r of a dielectric to the polarizability α of the molecules constituting the dielectric property. For a spherical homogeneous inclusion located in free space, the normalized dipole polarizability is [35], [36]

$$\alpha = 3 \frac{\epsilon_r - 1}{\epsilon_r + 2} \quad (7)$$

here ϵ_r is the relative permittivity of the sphere. In [27], this equation was generalized to an arbitrary background as

$$\alpha_{3D} = 3 \frac{\epsilon_t - \epsilon_b}{\epsilon_t + 2\epsilon_b} \quad (8)$$

where ϵ_t and ϵ_b are complex permittivities for the inclusion and background, respectively. The applicability of this formulation to the 3D case has been previously tested in [27]. We have modified (8) for the 2D case as [37]

$$\alpha_{2D} = 2 \frac{\epsilon_t - \epsilon_b}{\epsilon_t + \epsilon_b} \quad (9)$$

and α_{2D} now represents the normalized polarizability on a circle.

B. Verification criteria for the 2D DDA

Draine et al. [30] proposed a DDA-validity criteria for 3D geometries which relates wavelength k , refractive index m , and lattice spacing l , and is expressed as $ml|k|l \lesssim 1$. The refractive index is $m = \sqrt{\epsilon_r}$, where ϵ_r is the relative permittivity. In [32], the error of DDA for an arbitrary geometry in 3D have been discussed in detail. The shape of a scatterer and various derivations of the DDA have a direct impact on the accuracy of the results [32], [38]. For a general 3D geometry, if a scatterer is not only constructed from cubical sub-volumes, the error is bounded by the value of $|\sqrt{\epsilon_r}|k|l$.

We propose a similar criteria for the validity of the 2D DDA with a lossy background and the wavenumber in the form of (2). We let $\tilde{\epsilon}_r = \frac{\epsilon_t}{\epsilon_b}$, $\tilde{m} = \sqrt{\tilde{\epsilon}_r}$, and we obtain:

$$L := |\sqrt{\tilde{\epsilon}_r}|k_b|l \lesssim 1 \quad (10)$$

With this formulation we can ensure that the space discretization of our cubic geometry in Figure 3 is sufficiently small compared to our background wavenumber. Approximating a 2D square geometry with N dipoles as in Figure 3, the area of the square, S , is represented by Nl^2 , where $l = \sqrt{\frac{S}{N}}$. To approximate this 2D geometry with an adequate number of dipoles with respect to its radius, $r_s = \sqrt{S}$, the criteria (10) reduces to:

$$N > |\tilde{\epsilon}_r|(|k_b|r_s)^2 \quad (11)$$

For a circle with area of S_0 , this criteria converts to (12)

$$N > \pi \tilde{\epsilon}_r (|k_b| r_c)^2 \quad (12)$$

where $r_c = \sqrt{\frac{S_0}{\pi}}$. Based on the criteria (10), the optimum number of dipoles for our configuration based on the value of L is proposed and tested in our simulation set-up. In Figure 3, we show examples of different resolutions and how the geometry discretization affects the precision in modeling a circle as a scatterer since it is not conventionally constructed from cubes. By increasing the number of dipoles inside our imaging domain, the scatterer becomes better represented.

III. NUMERICAL AND EXPERIMENTAL STUDIES

A. Simplified Microwave Imaging Set-up

To model the 2D forward solution for the microwave imaging system with DDA, we considered an extended square modeling zone with the side length of 40 cm. The circular inclusion was centered at the origin with a diameter varying over an interval between 2 to 10 cm. The point source was located at $y = -0.0762$ (m), as shown in Figure 2. For these numerical studies, the relative permittivity of the background ($\epsilon_{r,b}$) was set to 22, and the relative permittivity for the inclusion ($\epsilon_{r,i}$) varied from 20 to 60. The conductivity was 1.0 (S/m) for the full domain, and the operating frequency was 1.3 GHz.

B. Numerical results

The electric field simulated with DDA and COMSOL Multiphysics for cases with different scattering inclusions are presented here. For this investigation, three different cases were studied:

1) Number of dipoles required to accurately represent the geometry: To represent the imaging domain with an adequate number of dipoles, we increased the sampling size similar to Figure 3 until criteria (10) was satisfied with the value of the $L = 0.87$ for 6561 dipole case. For the 441 and 1681 dipole cases L is 3.37 and 1.72, respectively. Figure 4 shows the forward solutions for the different configurations for a single, 2 cm diameter, $\epsilon_{r,i} = 40$ inclusion located at the origin. Figures 4(a) to 4(d) show the magnitude distributions for the 441, 1681 and 6561 dipole cases along with the COMSOL solution while Figures 4(e) to 4(h) illustrate the corresponding phase distributions. Figure 4 demonstrates that increasing the dipole number results in higher accuracy for magnitude and phase. Note that the differences in phase wrapping locations between the DDA and FE cases relate to differences in the assumptions of the source phases. Figure 5 shows comparisons of the amplitude and phase between two of the DDA sample sizes versus the FE solution plotted along a vertical line running through the source and inclusion (source located at $y = -0.0762$ (m)). For both plots, the values decrease monotonically with respect to position, with a noticeable perturbation where the inclusion is located. The phase is quite similar for all cases. The magnitude FE plot shows a definite perturbation near the site of the inclusion.

The 6561 dipole case is somewhat similar to the FE plot and is decidedly more accurate than the 1681 dipole case.

2) Accuracy of the DDA for different object sizes: We increased the object size from a diameter of 2 cm to 8 cm (keeping $\epsilon_{r,t} = 40$). Figure 6 shows the simulated magnitude and phase results for both the FE and DDA for number 6561 dipoles. Similarly to the previous case, the field patterns are quite consistent between the DDA and FE cases. It appears that the deviation in the magnitude plot near the object is more pronounced for the DDA than for the FE cases. This may be because the effective property distribution for the DDA is larger than that for the FE since it uses a node-based (or dipoles) distribution in the former and element-based distribution in the latter case. The plots in Figure 7 compare magnitudes and phases along a straight line through the source and object center for the 1681 and 6561 dipole DDA cases and the corresponding FE case. The trends are similar to the previous example where the 1681 dipole case does not adequately capture the perturbations, but the 6561 dipole case does. In this situation, for the magnitude plot, it appears that the 6561 dipole case overshoots the FE plot, but this is consistent with the previous observation concerning the effective property distribution size. For a broader measure of accuracy, the averaged relative errors for the entire field distribution between the DDA and FE solutions were computed. These show a proportional increase as the object size increases. The error improvement in going from the 441 to 1681 dipole cases is consistently only on the order of 10% for all object sizes; however, the improvement in error for jumping from the 1681 to 6561 meshes ranges from a factor of 1.5 to almost 4.

3) Accuracy of the DDA with respect to an increasing property contrast: We tested the accuracy of the DDA with respect to an increasing property contrast with object the permittivity growing to 60. Figure 8 shows magnitude and phase distributions for the 2 cm diameter object. These distributions are qualitatively quite similar to those for the previous examples with small differences between the DDA and FE plots. Figures 9 and 10 compare magnitudes and phases along a straight line through the source and object center for the 1681 and 6561 dipole DDA cases and the corresponding FE case. Similarly to the previous case, the overall trends are similar where the 1681 dipole case does not adequately capture the perturbations, but the 6561 dipole case does. The overshoot on the magnitude plot of the 6561 dipole case is also consistent with the previous observations concerning the effective distribution size. The averaged relative errors range from 0.015 to 0.139 for the 6561 mesh as the object permittivity increases from 30 to 60. The error improvement in going from the 441 to 1681 meshes is consistently only on the order of 30% for all contrast levels; however, the decrease in error in jumping from the 1681 to 6561 meshes ranges from a factor of 1.8 to 4.6.

C. The measurement set-up for the microwave imaging system

In Figure 1, the tank was filled with a liquid mixture of 80% glycerin and 20 % water. A cylinder of diameter 3 cm was positioned at the center of the imaging zone of the tank. The plastic cylinder was filled with the liquid mixture of 72% glycerin and 28% water. We set the conductivity of background and inclusion to 1.2810 and 1.4563 (S/m), respectively, and relative permittivity of background and inclusion to 22 and 35, respectively. These values are

chosen according to the electrical properties for glycerin and water mixtures shown in [39], and selected to mimic a real imaging case. Meaney et al. [39] have reported on permittivity and conductivity values for such mixtures in a frequency range up to 3 GHz. For these measurements, the output power was set to 0 dBm, and the operating frequency was 1.3 GHz. We calibrated the system by subtracting measured data for the homogeneous case from measured data acquired in the presence of the cylinder.

D. Measurement results

We compare measured data collected from the microwave imaging system to simulation. Figure 11 compares the calibrated magnitudes and unwrapped phases of the electric fields measured at each antenna location to those of the 2D DDA and FE. While both measured and computed magnitudes and phases demonstrate similar trends, there are differences in the main projections of each. For the phase, we note that because the property distribution of the actual cylinder is closer to that of the element-based FE model, we would expect some differences between the measurements and the 2D DDA model which utilizes a node-based representation. In addition, as noted in a recent study [40] examining microwave breast phantoms, impact of plastic cylinder is not insignificant. Given the low properties of the phantom shell material, our expectation is that it would act to lower the effective properties of the cylinder and subsequently generate less of a signal projection [40]. For magnitude data, the same issues will also contribute to the differences. In addition, because the measurements are in 3D while the model is in 2D, we expect some differences. Our experience is that phase values for 2D and 3D typically match reasonably well, but differences in magnitude values are more substantive [41]. Regardless, the overall trends are encouraging.

IV. CONCLUSION

By knowing the adequate number of dipoles based on (11) for representing our geometry, we can use the DDA as an alternative to other numerical methods previously used as forward solvers for the 2D electric field. The DDA, FE and measurements show comparable results in terms of both magnitude and phases. This method is also accurate for relatively large objects with high contrast permittivity properties. In this way, the 2D DDA can be used as a forward solver in reconstruction algorithms for microwave imaging. Our plan for the future is to utilize the 2D DDA to optimize our imaging algorithm with reduced computational time. The authors will be reporting on the computational aspects of the forward and inverse solvers in future works.

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Biographies

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Andreas Fhager (M'07) received the M.Sc. degree in engineering physics and the Ph.D. degree in electrical engineering from the Chalmers University of Technology, Gothenburg, Sweden, in 2001 and 2006, respectively. He was appointed Docent in Electrical Engineering at Chalmers University of Technology in 2011. His current research interests include electromagnetic imaging methods for breast cancer detection, stroke diagnostics, and other biomedical applications of microwaves.

Mikael Persson (M'10) received the M.Sc. and Ph.D. degrees from the Chalmers University of Technology, Gothenburg, Sweden, in 1982 and 1987, respectively. He became a Professor in Electromagnetics in 2000 and a Professor in Biomedical Electromagnetics in 2006 with the Department of Signals and Systems, Chalmers University of Technology, where he has been the Head of the Division of Signal Processing and Biomedical Engineering since 2010. He has authored and co-authored more than 200 refereed journal and conference papers. His current research interests include electromagnetic diagnostics and treatment.

Paul M. Meaney (M'91-SM'11-F'17) received the AB degree in electrical engineering and computer science from Brown University, Providence, RI, USA, in 1982, the masters degree in microwave engineering from the University of Massachusetts, Amherst, MA, USA, in 1985, and the Ph.D. degree from Dartmouth College, Hanover, NH, USA, in 1995. He was involved in the millimeter-wave industry with Millitech Corporation, South Deerfield, MA, USA, and Alpha Industries, Woburn, MA. He spent two years as a Post-Doctoral Fellow, including one year at the Royal Marsden Hospital, Sutton, U.K. He has been a Professor with Dartmouth College since 1997 and is also the President of Microwave Imaging System Technologies, Inc., Hanover, which he co-founded with Dr. K. D. Paulsen in 1995. He is also a Professor with the Signals and Systems Division, Chalmers University of Technology, Gothenburg, Sweden. The Dartmouth group has authored several clinical studies in various settings including breast cancer diagnosis, breast cancer chemotherapy monitoring, bone density imaging, and temperature monitoring during thermal therapy. He has also explored various commercial spin-off concepts, such as detecting explosive liquids and noninvasively testing whether a bottle of wine has gone bad. He has coauthored over 70 peer-reviewed journal papers, co-written 1 textbook and presented numerous invited papers related to microwave imaging, and holds 12 patents. His current research interests include microwave tomography, which exploits the many facets of dielectric properties in tissue and other media, and also include breast cancer imaging, where his group was the first to translate an actual system into the clinic.

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Fig. 1.
Photograph of the measurement set up including the tank, antennas and the phantom cylinders.

Fig. 2.

Schematic of 3D/2D forward model. An array of 16 monopole antennas are located within the 2D xy-plane. The transmitting antenna is colored in red.

Fig. 3. Diagrams of the 2D forward model domains utilizing (left) 441, and (right) 6561 dipoles, respectively.

Fig. 4.

Plots of the 1.3 GHz magnitude (top) and phase (bottom) distributions for the different dipole density cases compared with the FEM benchmarks, for the conductivity of the inclusion and background set to 1, background relative permittivity $\epsilon_{r,b} = 22$, and inclusion relative permittivity $\epsilon_{r,t} = 40$, $d = 2$ (cm).

Fig. 5.

Plots of magnitude and phase values on the line through the centre of the inclusion for $f=1.3$ GHz, $\sigma = 1$, $\epsilon_{r,b} = 22$, $\epsilon_{r,t} = 40$, $d = 2$ (cm).

Fig. 6. Plots of magnitude (top) and phase (bottom) distributions for $f=1.3$ GHz, $\sigma=1$, $\epsilon_{r,b}=22$, $\epsilon_{r,t}=40$, $d=6$ (cm).

Fig. 7.

Plots of magnitude and phase values on the line through the centre of the inclusion for $f=1.3$ GHz, $\sigma=1$, $\epsilon_{r,b}=22$, $\epsilon_{r,t}=40$, $d=6$ (cm).

Fig. 8.
Plots of magnitude (top) and phase (bottom) distributions for $f=1.3$ GHz, $\sigma=1$, $\epsilon_{r,b}=22$,
 $\epsilon_{r,l}=60$, $d=2$ (cm).

Fig. 9.

Plots of magnitude and phase values on the line through the centre of the inclusion for $f=1.3$ GHz, $\sigma = 1$, $\epsilon_{r,b} = 22$, $\epsilon_{r,t} = 60$, $d = 2$ (cm).

Fig. 10.
Plots of magnitude and phase values on the line through the centre of the inclusion for $f=1.3$ GHz, $\sigma = 1$, $\epsilon_{r,b} = 22$, $\epsilon_{r,t} = 60$, $d = 6$ (cm).

Fig. 11.
The magnitude and phase projection values at the antennas locations.