3-D Imaging of Inhomogeneous Materials Loaded in a Rectangular Waveguide

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***Abstract*—A Newton-type method for the reconstruction of inhomogeneous 3-D complex permittivity variation of arbitrary shaped materials loaded in a rectangular waveguide is presented. The problem is first formulated as a system of integral equations consist of the well-known *data* and *object equations*, which contain the dyadic Green's function of an empty rectangular waveguide. Two unknowns of this system are solved in an iterative fashion by linearizing one of them, i.e., the data equation in the sense of the Newton method, which corresponds to a first-order Taylor expansion of the related integral operator. Since the problem is severely ill posed by nature, a regularization in the sense of Tikhonov is applied to the data equation. A detailed numerical implementation of the method, together with some numerical examples are also given to show the capabilities and validation limits of the method.**

***Index Terms*—Inhomogeneous permittivity reconstruction, inverse problem, Newton method, rectangular waveguide.**

I. Introduction

PRECISE imaging of electromagnetic parameters of materials is a very important topic in electromagnetic and microwave theory since it has a wide range of applications in the areas of microwave devices, filter design, nondestructive testing, material science, biomedical applications, etc. The conventional problem in this subject is the determination of the permittivity of a homogeneous material, wherein it is possible to reach a huge number of studies in the open literature [1]–[16]. Classical approaches for this problem can be classified in three categories, which are: 1) free-space methods; 2) transmission line methods; and 3) waveguide methods. A more complicated problem compared to that of homogeneous materials is related to multilayered structures [17], [18]. The general approach in most of the studies mentioned above is based on the expression of the propagation constant inside the material in terms of measured scattering parameters of the structure under test. More recent works related to waveguide methods were usually based on neural-network- and genetic-based algorithms for different type of applications. For example, a neural-network approach for the profiles having 2-D variations was presented in [19], where the profiles have been approximated by linear, quadratic, or Gaussian base functions with a few coefficients, and very satisfactory numerical results have been reported. However, *a priori* knowledge of the functional variation of the actual profile is indispensable in this method. A nondestructive testing application for the determination of spherical inclusions in a homogeneous dielectric material is formulated in [20], again by the use of the neural-network method. In [21], a genetic algorithm combined with a gradient descent optimization method is applied to homogeneous or layered materials having different shapes and positions.

The more general and inclusive problem in this respect is the reconstruction of the complex permittivity distribution of an arbitrary shaped inhomogeneous material loaded in a waveguide. To the best of our knowledge, this problem has not been investigated enough in the open literature and it is open to new theoretical, as well as experimental, contributions. Furthermore, although this problem belongs, in principle, to the class of inverse problems, it is so far not investigated by the general and conventional integral-equation-based methods of inverse scattering theory, except in [22]–[24], wherein [22] and [23]were related to 1-D structures, while in [24], an immature theory and the very preliminary results for the 3-D case were presented as a conference abstract. Eventually the general integral-equation-based inverse-scattering approach to the problem with a detailed analysis will be an initiative work for further developments in the 3-D case.

Within this framework, the main aim of this study is to address the theoretical and numerical analysis of the 3-D imaging problem related to inhomogeneous lossy materials located in a rectangular waveguide by an inverse scattering formalism, which is based on the Newton iterative algorithm. Along this direction, an empty rectangular waveguide is taken into consideration, which is to be filled with an inhomogeneous material whose permittivity distribution may have an arbitrary variation in spatial coordinates. The problem is then formulated as an inverse scattering one by considering the well-known data and object equations written in terms of the object function and the electric field distribution inside the waveguide. The data, which should be provided by real measurements in practical applications, are obtained by solving the direct problem through the finite-difference time-domain (FDTD) method, which also prevents us from the inverse crime. It is also worth mentioning that the method given in this study allows one to use both the dominant and/or higher order modes for the excitation, where, in fact, even in the dominant mode excitation, the higher order modes may exist since the geometrical and physical properties of the material are assumed to have arbitrary variations.

In the application of the method, the first the data equation that connects the measured scattered field and the unknown in-

Manuscript received August 04, 2009. First published April 08, 2010; current version published May 12, 2010.This work was supported by The Scientific and Technological Research Council of Turkey (TUBITAK) under Grant 108E146.

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Digital Object Identifier 10.1109/TMTT.2010.2045528

homogeneous permittivity distribution is written in an operator form in terms of a vectorial density function, which is defined by the multiplication of the object function and the total electric field. An initial estimate of the density function is then obtained via the back propagation algorithm [25]. By the use of this initial guess, the total electric field inside the reconstruction region is calculated from the object equation through a standard 3-D numeric integration. The first approximation of the object function is then determined using the known values of the vectorial density function and the total electric field vector in a least square sense. The rest of the algorithm is an iterative one by nature, i.e., the data equation is linearized in terms of the object function through the Frechét derivative of the related operator and then the updated density function corresponding to the update of the object function is calculated. The updated density function is substituted in the object equation in order to find the new electric field vector inside the object. From the knowledge of the updated field and density functions, the object function is again calculated in a least square sense. This iteration scheme is continued until a desired level of accuracy is obtained. Since the data equation is an ill-posed one, Tikhonov regularization in each iteration step is applied where the regularization parameter is calculated by Morozov's discrepancy principle [26]. In order to show the applicability, as well as the limitations of the method, some illustrative numerical examples are presented. The preliminary numerical examples showed that this conventional basic method, which is comprehensively applied to open region problems, is also applicable to a waveguide problem even in the case of a very limited number of data. Although the method yields quite satisfactory results, especially for smooth and continuous variations, the sharp changes in both geometrical and physical properties of the material cannot be reconstructed properly, even though it is not an intrinsic limitation of the method.

In Section II the general formulation of the problem is presented by introducing the data and object equations. Section III is devoted to the solution of the inverse problem, while in Section IV some numerical simulations are given. Finally, conclusions and some comments are presented in Section V. Time convention is assumed as $e^{-i\omega t}$ and omitted from now on.

II. General Formulation of the Problem

Consider the geometry shown in Fig. 1, where a rectangular waveguide with dimensions $a \times b$ is loaded with a nonmagnetic $(\mu = \mu_0)$ object D, having inhomogeneous relative dielectric permittivity $\varepsilon_r(r)$ and conductivity $\sigma(r)$, where $r = (x, y, z)$ denotes the position vector of any point in waveguide. Without loss of generality, it can be assumed that the object D may also be composed of disjoint bodies. Let us denote the incident, scattered, and total electric field vectors inside the waveguide by $\vec{E}_i, \vec{E}_s$ and $\vec{E}$, respectively. Here, the incident field $\vec{E}_i$ corresponds to an electric field vector inside the empty waveguide for a chosen exciting case, while $\vec{E}$ is the total electric field in the waveguide, which is loaded by an arbitrary shaped inhomogeneous dielectric material. Thus, the field defined by

$$\vec{E}_s(r) = \vec{E}(r) - \vec{E}_i(r) \tag{1}$$

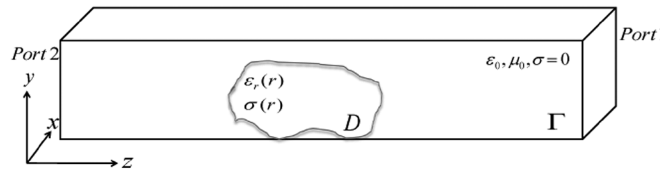

Fig. 1. Geometry of the problem: rectangular waveguide loaded with an arbitrary shaped inhomogeneous material.

can be considered as the contribution of the inhomogeneous 3-D body to the total field. From the above definitions, together with wave equation in the waveguide and using Green's theorem, one has the following two integral equations:

$$\vec{E}(r) = \vec{E}_i(r) + k_0^2 \int_D \bar{G}(r; r')\vec{E}(r')v(r')dv', \qquad r \in D \tag{2}$$

$$\vec{E}^s(r) = k_0^2 \int_D \bar{G}(r; r')\vec{E}(r')v(r')dv', \qquad r \in \Gamma \tag{3}$$

which are known as *object* and *data equations*, respectively. In (2) and (3), $\bar{G}$ denotes the dyadic Green's function of the empty rectangular waveguide whose explicit expression can be found in [27], which will not be repeated again here for the sake of brevity. The function $v(r)$ appearing in (2) and (3) is the object function defined as

$$v(r) = \frac{k^2(r)}{{k_0}^2} - 1 \tag{4}$$

where $k(r)$ denotes the wavenumber of any point in the loaded waveguide whose square is expressed as

$$k^2(r) = \begin{cases} \omega^2\varepsilon_r(r)\varepsilon_0\mu_0 + i\omega\sigma(r)\mu_0, & r \in D \\ {k_0}^2 = \omega^2\varepsilon_0\mu_0, & \text{otherwise} \end{cases} \tag{5}$$

for a given angular frequency ω.

Note that (2) and (3) are written for the points inside and outside the inhomogeneous object, respectively. In (3), Γ denotes any region outside the inhomogeneous body, which actually corresponds to the measurement domain. In practical applications, Γ consists of two points (Port 1 and Port 2) corresponding the so-called S-parameters measurement setup. The waveguide problem whose geometrical configuration is given in Fig. 1 is represented by the system of integral equations given by (2) and (3), and therefore, they can be used for solving both direct and inverse problems. In the direct problem, the function $v(r)$, i.e., the material properties, are known and the electric field distribution is to be determined at any point inside the waveguide, while in the inverse problem, $\vec{E}_s(r)$ is known at some points outside the inhomogeneous object and the function $v(r)$ is to be determined. It is clear from the definition of the object function given by (4) that $v(r)$ vanishes for the points outside the body under test. Therefore, at least theoretically the support of the object function also determines the boundary of the object.

III. Newton-Based Reconstruction Method

In this section, we will present a Newton-based algorithm in order to reconstruct the variation of the permittivity and conductivity of the object located in rectangular waveguide. To this aim, let us first define a vectorial density function, which indeed corresponds to a kind of current source distribution—except a complex constant factor—as the multiplication of the total electric field vector and the object function by

$$\mathbf{\Phi_j}(r) = v_j(r)\vec{E}_j(r), \qquad j = 1, 2, \ldots, Q \tag{6}$$

in which the index j is used to represent different frequencies within a chosen exciting frequency band. Since the imaginary part of the object function is dependent on the frequency, it will be convenient to use the following normalization [25]:

$$v_j(r) = \mathrm{Re}[\bar{v}(r)] + i\frac{\bar{\omega}}{\omega_j}\mathrm{Im}[\bar{v}(r)], \qquad j = 1, 2, \ldots, Q \tag{7}$$

where $\bar{\omega}$ is the minimum frequency in the working frequency interval.

The data equation can now be written in a compact form as follows:

$$\mathbf{F_j}(\mathbf{\Phi_j}) = \vec{E}_j^s \tag{8}$$

where the operator $\mathbf{F_j}$ is defined by

$$\mathbf{F_j}(\mathbf{\Phi_j}) = k_0^2 \int_D \bar{G}_j(r; r')\mathbf{\Phi_j}(r')dv', \quad r \in \Gamma; \quad j = 1, 2, \ldots, Q. \tag{9}$$

Note that all integral operators in the formulation are numerically approximated by corresponding matrices through the discretization of the integration domain. In the discretization procedure, the integration domain is divided into small rectangular prism-shaped cells and all the functions, except the dyadic Green's function, are assumed to have constant values inside the cells. The integration of slowly convergent series appearing in dyadic Green's function in 3-D small cells of the reconstruction domain is achieved by the partial summation technique, as explained in [27].

In order to determine the initial variations of $v(r)$ and $\vec{E}(r)$, which will be used in the Newton iterative algorithm, we first apply the back propagation method [25] to obtain the initial value of density function as

$$\mathbf{\Phi_j^{(0)}} = \frac{\|\mathbf{F_j^*}(\vec{E}_j^s)\|^2}{\|\mathbf{F_j}\left(\mathbf{F_j^*}\left(\vec{E}_j^s\right)\right)\|^2}\mathbf{F_j^*}(\vec{E}_j^s) \tag{10}$$

where $\mathbf{F_j^*}$ is the adjoint of the operator $\mathbf{F_j}$, and the norms appearing in [10] are ℓ_2 norms of the matrices corresponding to the 3-D integral operators. One can then easily substitute this function into an object equation and perform a classical 3-D numerical integration to obtain the initial guess of the total electric field as

$$\vec{E}_j^{(0)} = \vec{E}_i(r) + k_0^2 \int_D \bar{G}(r; r')\mathbf{\Phi_j^{(0)}}(r')dv', \qquad r \in D. \tag{11}$$

Before going into the details of the algorithm, it will be convenient to mention that the relation given by (6) constitutes an overdetermined system for $v(r)$ since the object function $v(r)$ is a scalar one. Although the co-polarized components of the vectors dominate this vectorial relation, especially in the fully filling case, we prefer to solve the object function from this equation by a least square algorithm in order to take the advantage of additional data coming from cross-polarized components. Also, we force the initial guess to be a complex constant in order to avoid unstable values, which may lead divergent results in the application of the Newton method. Therefore, in a least square sense, an average initial value of the object function can be written as

$$\mathrm{Re}\left(v^{(0)}\right) = \frac{\sum_{n=1}^{N}\sum_{j=1}^{Q}\sum_{k=1}^{3}\mathrm{Re}\left(\Phi_{n,j,k}^{(0)}\bar{E}_{n,j,k}^{(0)}\right)}{\sum_{n=1}^{N}\sum_{j=1}^{Q}\sum_{k=1}^{3}\left(E_{n,j,k}^{(0)}\bar{E}_{n,j,k}^{(0)}\right)} \tag{12}$$

$$\mathrm{Im}\left(v^{(0)}\right) = \frac{\sum_{n=1}^{N}\sum_{j=1}^{Q}\sum_{k=1}^{3}\left(\frac{\bar{\omega}}{\omega_j}\right)\mathrm{Im}\left(\Phi_{n,j,k}^{(0)}\bar{E}_{n,j,k}^{(0)}\right)}{\sum_{n=1}^{N}\sum_{j=1}^{Q}\sum_{k=1}^{3}\left(\frac{\bar{\omega}}{\omega_j}\right)^2\left(E_{n,j,k}^{(0)}\bar{E}_{n,j,k}^{(0)}\right)}. \tag{13}$$

Here, $\bar{}$, $k = 1, 2, 3$, and N denote the complex conjugate, unit vectors x, y, z, and the number of subcells of the discretized volume of the object under test, respectively. Using these initial variations it is possible to give an iterative algorithm, which is based on the linearization of the data equation in the Newton sense as

$$\mathbf{F_j}\left(\mathbf{\Phi}_j^0\right) + \mathbf{F_j'}(\boldsymbol{\delta\Phi_j}) = \vec{E}_j^s \tag{14}$$

where $\mathbf{F_j'}$ in (14) is the Frechét derivative of the operator $\mathbf{F_j}$ defined by

$$\mathbf{F_j'}(\boldsymbol{\delta\Phi_j}) = k_0^2 \int_D \bar{G}_j(r; r')\vec{E}_j^{(0)}(r')\delta v(r')dv', \qquad r \in \Gamma \tag{15}$$

where

$$\delta\Phi_j(r) = \vec{E}_j^0(r)\delta v(r). \tag{16}$$

Here, the function $\delta v(r)$ corresponds to the update amount of the object function. Equation (14) is a Fredholm integral equation of the first kind with respect to $\delta\Phi_j(r)$ and it is severely ill posed. In order to obtain a stable solution, we apply the well-known Tikhonov regularization in which the regularization parameter γ is determined by Morozov's discrepancy principle [26] based on the estimated power noise. The regularized solution of (14) can then be given as

$$\delta\Phi_j(r) = [\gamma\mathbf{I} + \mathbf{F_j'^*}\mathbf{F_j'}]^{-1}\left[\mathbf{F_j'^*}\left(\mathbf{\vec{E}}_j^s - \mathbf{F_j}\left(\Phi_j^0\right)\right)\right] \tag{17}$$

where $\mathbf{I}$ denotes the identity operator. Now the updated density function is substituted into the object equation to obtain the updated total electric field. Again, by using a least square method, one can get δv as

$$\mathrm{Re}(\delta v(r)) = \frac{\sum_{j=1}^{Q}\sum_{k=1}^{3}\mathrm{Re}\left(\delta\Phi_{j,k}^{(0)}\bar{E}_{j,k}^{(0)}\right)}{\sum_{j=1}^{Q}\sum_{k=1}^{3}E_{j,k}^{(0)}\bar{E}_{j,k}^{(0)}} \tag{18}$$

$$\mathrm{Im}(\delta v(r)) = \frac{\sum_{j=1}^{Q}\sum_{k=1}^{3}\left(\frac{\bar{\omega}}{\omega_j}\right)\mathrm{Im}\left(\delta\Phi_{j,k}^{(0)}\bar{E}_{j,k}^{(0)}\right)}{\sum_{j=1}^{Q}\sum_{k=1}^{3}\left(\frac{\bar{\omega}}{\omega_j}\right)^2 E_{j,k}^{(0)}\bar{E}_{j,k}^{(0)}}. \tag{19}$$

Now the object function can be updated easily as $v^{(1)} = v^{(0)} + \delta v(r)$ and the total electric field can be updated through solving the object (2). The above iteration is continued until the norm of $\delta v(r)/v(r)$ becomes smaller than a predefined real number.

IV. Numerical Applications

In this section, we present some numerical results in order to validate the method as well as to see the effects of some parameters on the results. In all simulations, a cross section of the waveguide is chosen as $a = 7.2$ cm and $b = 3.4$ cm, which allows single mode propagation between 2.0833 and 4.1667 GHz. To be able to model more realistic cases, a random term

$$\tilde{E}_{j,k}^{s} = \xi|E_{j,k}^{s}|e^{i2\pi r_n} \tag{20}$$

is added to the simulated data of the scattered field, where ξ is the noise level and r_n's are normally distributed random numbers.

As a first example, we consider an inhomogeneous lossy dielectric rectangular prism, which is placed in $(x,y,z) \in [2,4] \times [0,2] \times [0,4]$ cm^3. The real and imaginary parts of the object function of the material under test vary linearly and sinusoidally along the z-axis, respectively. The reflected and transmitted fields are assumed to be measured at two points defined by $x = a/2; y = b/2; z = -10$ cm and $x = a/2; y = b/2; z = 10$ cm, respectively, for TE_{10} excitation. Exact and reconstructed variations of real and imaginary parts of the object function are given in Figs. 2 and 3. The results are plotted for five different $y =$ constant values corresponding to different slices. The operating frequency and the number of subcells are chosen as $f = 2.5$ GHz and $N = 250$, respectively, while the noise level is $\xi = 0.01$ and the number of iterations is nine. In order to show the convergency rate of the method, the ℓ_2 norm of $\delta v(r)/v(r)$ with respect to the iteration number is shown in Fig. 4. Through the results, one can observe that the method is quite capable of reconstructing smoothly varying profiles even with only two data.

In the second example, the proposed method is applied to a three-layer dielectric profile placed in $(x,y,z) \in [2,3.2] \times [0,1.2] \times [0,4.5]$ cm^3, where the waveguide is excited by the dominant mode. The reflected and transmitted fields are again assumed to be measured at the points defined by $x = a/2; y = b/2; z = -10$ cm and $x = a/2; y = b/2; z = 10$ cm. In Figs. 5 and 6, the exact and reconstructed profiles, which are obtained for $N = 300$, $\xi = 0.02$, and iteration number 98, are plotted where the number of operating frequency is chosen as $Q = 9$ in a range of $f = 2.5$–3.5 GHz. It is obvious from the results that

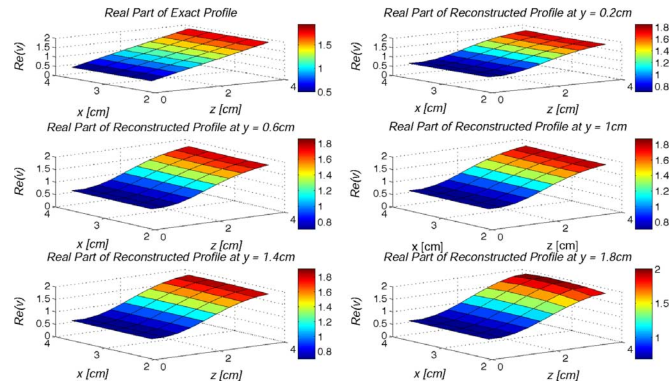

Fig. 2. Exact and reconstructed profiles of an inhomogeneous material having linearly varying real part for five different y slices.

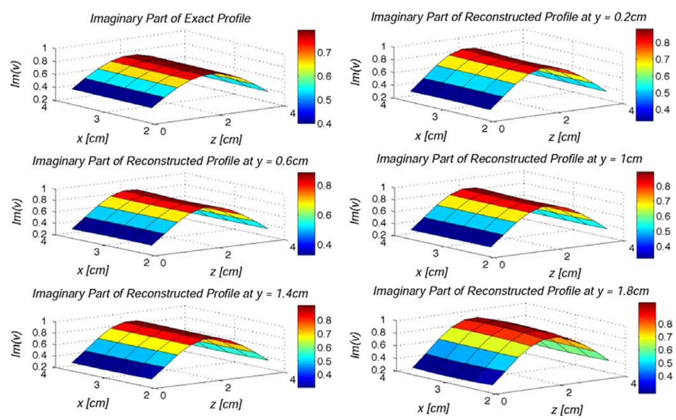

Fig. 3. Exact and reconstructed profiles of an inhomogeneous material having sinusoidally varying imaginary part for five different y slices.

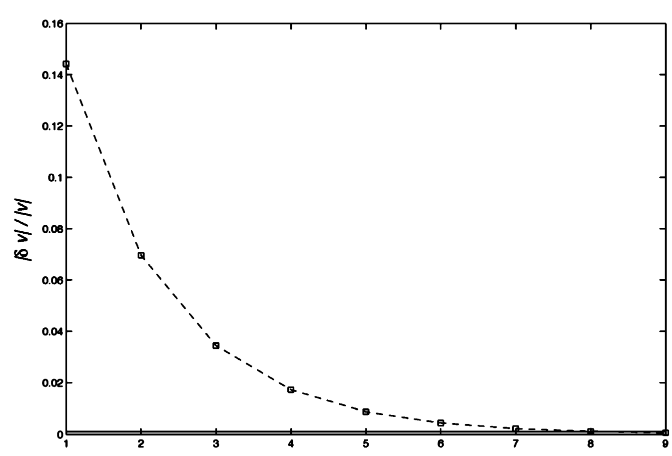

Fig. 4. Variation of the norm of the normalized update of object function versus iteration number.

the method is not capable of catching the sharp transitions, but gives a smoothed approximation of the original profile.

In the third example, we consider a lossless dielectric material having 2-D sharp variation, which is placed in $(x,y,z) \in [1,2.2] \times [0,0.6] \times [1,2.2]$ cm^3. From the numerical implementations, it is first observed that such a kind of structure cannot be reconstructed properly using only two data, therefore, we assume that the reflected and transmitted fields are measured at

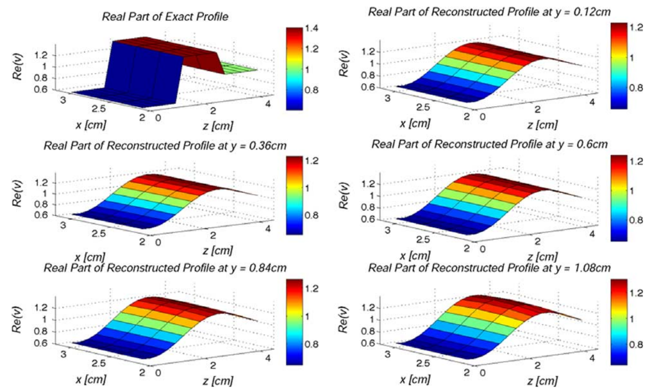

Fig. 5. Exact and reconstructed profiles of the three-layer material: real part of $v(r)$ for five different y slices.

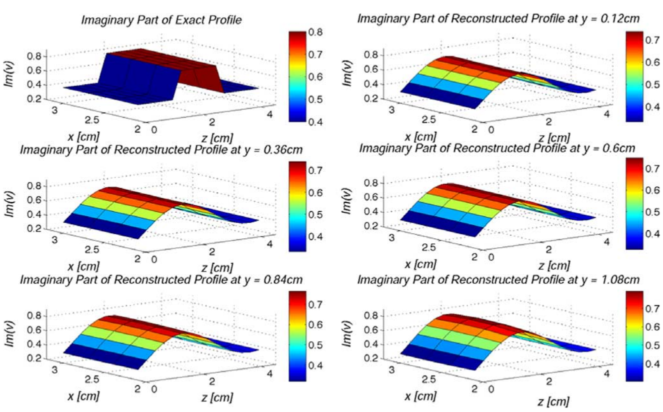

Fig. 6. Exact and reconstructed profiles of the three-layer material: imaginary part of $v(r)$ for five different y slices.

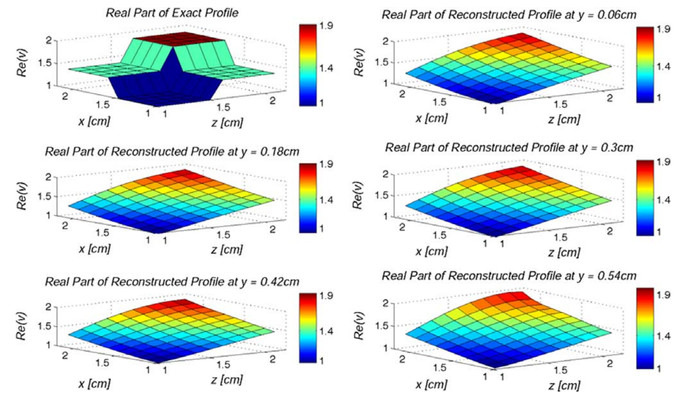

Fig. 7. Exact and reconstructed profiles of an inhomogeneous material having sharp variations for $\xi = 0.03$ and $f = 6$ GHz.

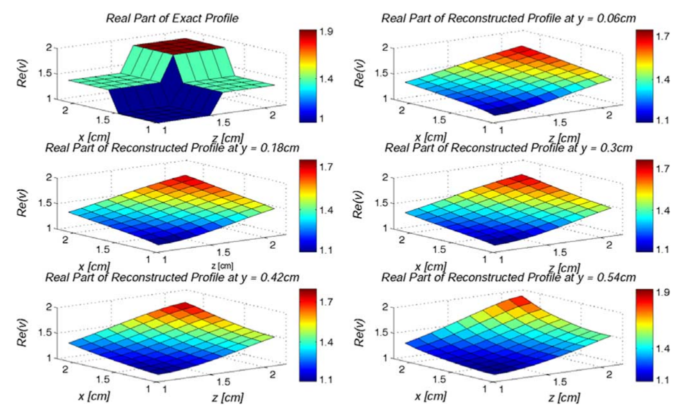

Fig. 8. Exact and reconstructed profiles of an inhomogeneous material having sharp variations for $\xi = 0.1$ and $Q = 9$ in a range of $f = 5$–6 GHz.

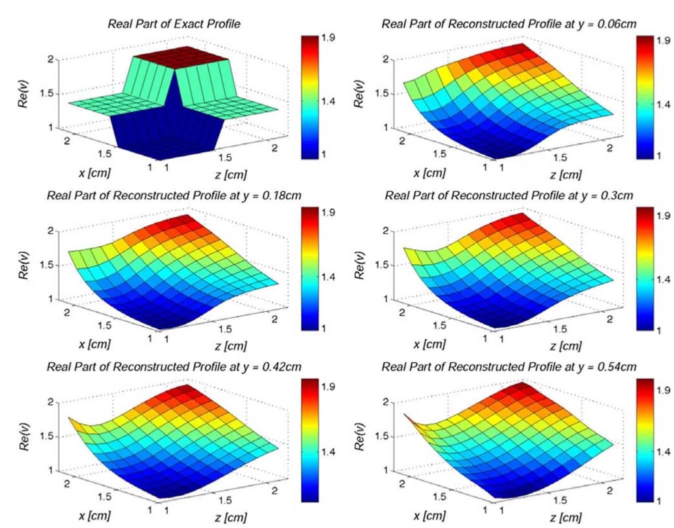

Fig. 9. Exact and reconstructed profiles of an inhomogeneous material having sharp variations: $\xi = 0.03$ and $f = 9$ GHz.

$4 \times 3 = 12$ equidistant points defined in the regions $(x, y) \in [1.5, 4.5] \times [1, 3]$ cm^2, $z = -10$ cm and $(x, y) \in [1.5, 4.5] \times [1, 3]$ cm^2, $z = 10$ cm. The exact and reconstructed profiles, which are obtained for $N = 500$, $f = 6$ GHz, $\xi = 0.03$, and iteration number 20, are presented in Fig. 7. It should be noted that all the propagating modes are excited in this example. It can be seen from the reconstructions that the method gives only a rough approximation of the actual profile. On the other hand, it is also observed through the numerical applications that multifrequency measurements do not improve the results for the given parameters, while the results start to deteriorate for higher noise levels. In order to show that the effect of higher noise levels can be reduced by multifrequency measurements, a previous example is again considered with the same parameters, except for the noise level of $\xi = 0.1$, the number of the chosen frequencies $Q = 9$ in a range of $f = 5 - 6$ GHz, and iteration number of 121. The exact and reconstructed profiles are shown in Fig. 8, which shows that the multifrequency measurements makes the method robust against noise.

The final example is devoted to show that the reconstruction quality can be enhanced by using higher frequencies, especially for sharp variations. Thus, we reconsider the profile in the previous example and apply the method for a single frequency of $f = 9$ GHz with the data measured at same points and contaminated with a noise of level $\xi = 0.03$. The number of cells for this case is chosen as $N = 720$. Note that all the propagating modes are included in the excitation. The reconstructions that show a satisfactory improvement compared to lower frequency results are demonstrated in Fig. 9.

V. Conclusion

In this study, the reconstruction problem related to 3-D arbitrary-shaped inhomogeneous lossy dielectric materials located in a rectangular waveguide is theoretically and numerically investigated by an inverse scattering formalism through the well-known Newton iterative algorithm. The problem is first reduced to the solution of a coupled system of integral equations by the aid of dyadic Green's function of the empty waveguide. The integral operators are then discretized to reduce the problem into matrix systems, which are solved through standard techniques. From the numerical implementations, it is shown that the preliminary results are promising, even though the method have certain validation limits. Furthermore, very satisfactory results are obtained, especially for smoothly varying profiles. It is also observed that the method is very sensitive to the noisy data in single frequency measurement case. However, this sensitivity can be readily reduced by the use of multifrequency measurements, as shown in numerical results. Another issue that is worth noting is that the resolution of the method can be enhanced by using higher frequencies for the profiles having abrupt changes in their geometrical or physical properties. It should be mentioned as a final note that although the results presented in this study initially seem very satisfactory for a 3-D reconstruction problem, the method should be improved so as to be applicable with real measurement setup, and it should certainly be tested against real data. Further studies will be developed in this direction.

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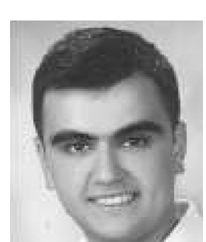

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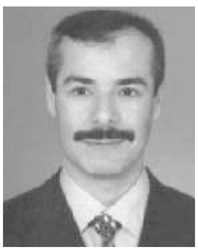

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