§42-19 Microwave Diagnostics of Dielectric Object

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Diagnostic imaging was uniquely developed in plasma diagnostics and it contributed to investigation in plasma physics last past decades. Computed Tomography (CT) was invented by A. M. Cormack in 1963. It was utilized for x-ray tomography in medical science, and many types of medical imaging diagnostics were invented until today. In plasma diagnostics, the x-ray tomography was reconstructed in PLT and JET for the 70's and 80's, and Electron Cyclotron Emission (ECE) CT was developed in TFTR in the 90's. Recently Microwave imaging diagnostics without CT method has been developed in TEXTOR, LHD, KSTAR and DIII-D [1]. It works as a microwave camera which records the microwave movie on a focal plane of optics. These advanced imaging techniques are well developed for plasma research.

An analysis method of microwave tomography is under consideration in order to determine the complex permittivity profile in a semi-transparent weak scattering object. The complex permittivity profile of the object is directly calculated by solving a nonlinear complex matrix equation. The scattering wave can be described in the first Born approximation as Eq (1).

$$e_l(\mathbf{r}) = e_l^i(\mathbf{r}) + \iint_S k_0^2 C(\mathbf{r}') e_l(\mathbf{r}') G(\mathbf{r},\mathbf{r}') d\mathbf{r}' \qquad (1)$$

$e_l(\boldsymbol{r})$ is total electric field, $e_l^i(\mathbf{r})$ is incident electric field, k_0 is wave number, $G(\mathbf{r},\mathbf{r}')$ is Green's function. The object and its surrounding area are separated by N pixels as shown in the figure 1. T_X is transmitter, R_X is receiver. The contrast function is defined to be complex permittivity difference between the object and its surrounding area as $C(\mathbf{r}) = \varepsilon(\mathbf{r}) - \varepsilon_{exp}$. The complex matrix equation is obtained by discretizing (1) and by solving it for the contrast function matrix as Eq (2).

$$\mathbf{C} = (k_o^2 \mathbf{G}_l^S \mathbf{E}_l \mathbf{C})^{-1} \mathbf{e}_l^S, \quad \mathbf{E}_l = \mathbf{I}(\mathbf{I} - k_o^2 \mathbf{G}\mathbf{C})^{-1} \mathbf{e}_l^i \qquad (2)$$

$e_l^s(\mathbf{r})$ is scattering electric field, $\mathbf{G}_l^S$ is Green's function for the scattering wave, and $\mathbf{I}$ is a unit matrix. In the weak scattering approximation, the matrix $\mathbf{E}_l$ is equal to the incident electric field matrix $\mathbf{I}e_l^i$. When the complex amplitude of the measured microwave is substituted into Eq (2), the contrast function matrix $\mathbf{C}$ and the complex permittivity $\varepsilon(\mathbf{r})$ can be obtained numerically. The first Born approximation is not applicable to higher dielectric object, and some additional procedures are necessary in such cases.

Several reconstruction programs of permittivity images for high dielectric object were described by the programing language of "python" in last year. The most efficient procedure is iteration for precise estimation of the total electric field in the analyzed region. Measurable range of the contrast ratio of the permittivity in CT image is $\varepsilon(\mathbf{r})/\varepsilon_{ext}$ =1.00±0.15 by the first Born approximation, much higher contrast ratio $\varepsilon(\mathbf{r})/\varepsilon_{ext} > 10$ is necessary in industrial applications. Higher permittivity contrast is advantageous to clearer permittivity image, but the image border is obscure without correction of wavelength contraction in the program. An iterative method is necessary to solve the problems. Total electric field and permittivity profile in the permittivity image are alternately modified to be more precise in the iterative method. At first step the total electric field in the scattering integral is assumed to be equal to that of the illumination wave. The permittivity profile is approximately calculated in this assumption by using the reconstruction programs. The initial electric field is modified by the approximate permittivity profile, and the modified electric field is utilized for the calculation of the permittivity profile in the next step of the reconstruction process. The most precise permittivity profile is calculated by the iterative process with the Single Value Decomposition (SVD) method.

Two types of the permittivity images are acquired by using the Born approximation method and the back projection method. The former is shown in left image in figure 2 and the latter is in right image. The object is an acrylic cylinder solid with the diameter of 1.2 cm (0.4λ) in air. The illumination wave is plane wave with the 10 GHz frequency and Gaussian beam profile. The permittivity image shows almost circular cross section obscurely in the case of the Born approximation. The obscure image may be caused by too small number of the data (measurement points of the scattering wave). The problem will be overcome by the improvement of the receiver system easily in future work. The permittivity image shows a striped pattern in the case of back projection method. The striped pattern may be caused by the hypothetical interference among the scattered waves in the time-reversal. A spatial filter for CT deconvolution may become helpful to erase the striped pattern of an artifact.

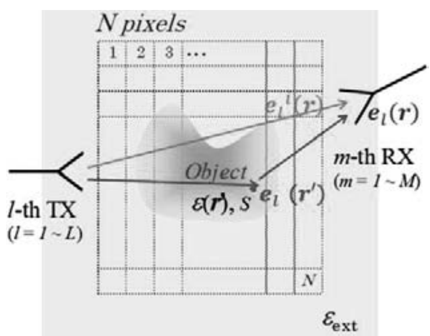

Fig. 1 Scattering model based on the first Born approximation

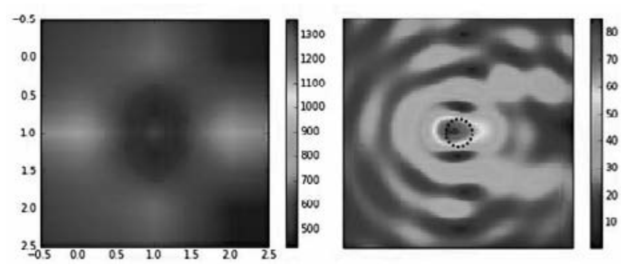

Fig. 2 Permittivity image calculated by the Born approximation (left) and the back projection image calculated of scattered wave (right).

1) B. Tobias. et al.: Plasma Fusion Res. **6** (2011) 2106042.