Enhancement of Resolution in Electromagnetic Imaging of Lossy Dielectric Objects Using a Slab of Left-Handed Material

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Introduction

Electromagnetic inverse scattering has found wide applications in sensing and remote sensing problems, for example, in nondestructive testing, geophysical probing, medical imaging, and target identifications. The Born approximation [1] is a simple and efficient linearized method, which has been widely used to solve free- and half-space problems from weak scatterers. In [2], the physical reason for the super-resolution phenomenon was investigated using different electromagnetic inverse scattering methods.

In this paper, we make use of the special physical characteristics of novel artificial left-handed materials (LHM) to realize the super resolution. In 1968, Veselago first proposed the concept of LHM [3]. One of the most attractive features of LHM is the amplification of evanescent waves. Using such a feature, it has been shown that strong surface waves can be excited near the boundaries of LHM slab with small loss [4–6]. We will investigate the possibility to enhance the resolution of dielectric objects using the LHM slab. The Born approximation has been used to solve the linearized inverse scattering problem. Numerical simulations show that better resolution can be achieved when the LHM slab is involved than those without the LHM slab. The study has demonstrated that the amplification of evanescent waves in the measurement data and inversion algorithm is the main reason for the super resolution.

General Theory

Consider the inverse-scattering theory for two-dimensional (2D) dielectric objects using the LHM slab. The problem to be considered is shown in Fig. 1. We use multiple line sources as transmitters and receivers to collect the scattered data. For a transmitter located at (x_t, z_t) where $z_t = -d_2$, the electric field in Region 2 can be written as

$$E_y^{inc}(\mathbf{r}, \mathbf{r}_t) = i\eta_0 I_t g_t^+(\mathbf{r}, \mathbf{r}_t), \tag{1}$$

which is just the incident field of the dielectric objects. Under the excitation of such an incident field, there will be electric fields $E_y(\mathbf{r}, \mathbf{r}_t)$ induced inside the dielectric objects D. From the EM theory, we can easily obtain the scattered electric fields due to $E_y(\mathbf{r}, \mathbf{r}_t)$. When the receivers are located at the same side of transmitters

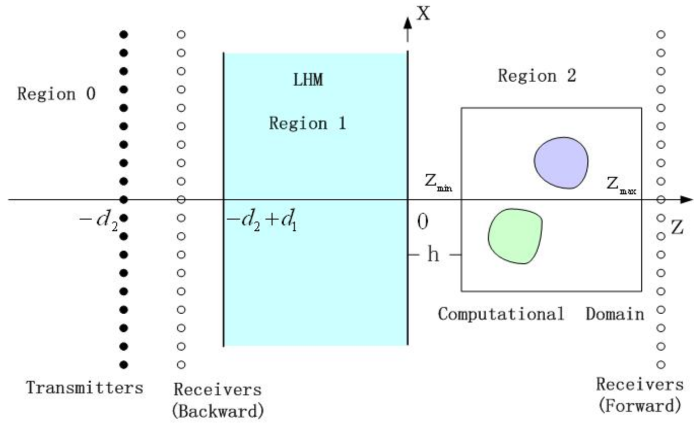

Figure 1: A general problem consisting of multiple transmitters, multiple receivers, a LHM slab, and dielectric objects to be reconstructed.

(backward receivers), we have

$$E^{sca}_{back}(\mathbf{r}_r, \mathbf{r}_t) = k_0^2 \int_D d\mathbf{r}\ g_t^-(\mathbf{r}_r, \mathbf{r}) E_y(\mathbf{r}, \mathbf{r}_t) O(\mathbf{r}); \tag{2}$$

when the receivers are located at the other side of transmitters (forward receivers), we have

$$E^{sca}_{forward}(\mathbf{r}_r, \mathbf{r}_t) = k_0^2 \int_D d\mathbf{r}\ g_r(\mathbf{r}_r, \mathbf{r}) E_y(\mathbf{r}, \mathbf{r}_t) O(\mathbf{r}), \tag{3}$$

where the Green's functions $g_t^+(\mathbf{r}, \mathbf{r}_t), g_r(\mathbf{r}_r, \mathbf{r})$ and $g_t^-(\mathbf{r}_r, \mathbf{r})$ involved in the LHM slab have been derived in [6]. In the above expressions,

$$O(\mathbf{r}) = \widetilde{\epsilon_r}(\mathbf{r}) - 1 \tag{4}$$

is the object function to be reconstructed, in which $\widetilde{\epsilon_r}(x, z) = \epsilon_r(x, z) + i\eta_0\sigma(x, z)/k_0$ is the relative complex permittivity of the dielectric objects, and k_0 and η_0 are wavenumber and wave impedance of free space, respectively. Here, $\epsilon_r(x, z)$ and $\sigma(x, z)$ represent the relative permittivity and conductivity of the dielectric objects.

Equations (2) and (3) can be generally written as

$$E^{sca}(\mathbf{r}_r, \mathbf{r}_t) = k_0^2 \int_D d\mathbf{r}\ g(\mathbf{r}_r, \mathbf{r}) E_y(\mathbf{r}, \mathbf{r}_t) O(\mathbf{r}). \tag{5}$$

Under the Born approximation, the internal electric field $E_y(\mathbf{r}, \mathbf{r}_t)$ can be replaced by the incident electric field, which results in a linearized inverse scattering described as

$$E^{sca}(\mathbf{r}_r, \mathbf{r}_t) = k_0^2 \int_D d\mathbf{r}\ g(\mathbf{r}_r, \mathbf{r}) E_y^{inc}(\mathbf{r}, \mathbf{r}_t) O(\mathbf{r}). \tag{6}$$

The above equation can be easily solved using the Tikhonov regularization technique.

Numerical Experiments and Discussions

In the following numerical examples, the LHM slab is characterized as $\epsilon_{r1} = -1 + 10^{-4} + i10^{-6}$ and $\mu_r = -1 + 10^{-4} + i10^{-6}$, which is resided at $d_1 = 0.2$ m and $d_2 = 0.6$ m, as shown in Fig. 1. The working frequency is 0.6 GHz. The reconstruction domain is a $0.5 \times 0.5m^2$ square region, and $h = 0.01$ m. The reconstruction domain is divided by $32 \times 32 = 1024$ pixels. 35 transmitters, 35 backward receivers and 35 forward receivers are placed on the measurement lines located at $z = -0.6$ m, -0.5 m, and 0.52 m, respectively, to collect scattered data over the range of 2 m. The scattered data are simulated using the accurate CG-FFT algorithm. The original object profiles to be reconstructed are shown in Fig. 2, where two square dielectric objects ($\epsilon_r = 2, \sigma = 0.01\ S/m$) are located in free space. Figure 3 illustrates the reconstructed profiles of permittivity and conductivity with the LHM slab.

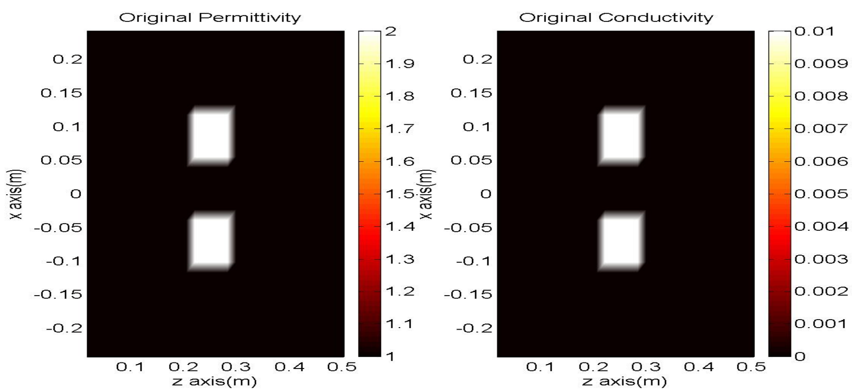

Figure 2: The original profiles of two dielectric objects.

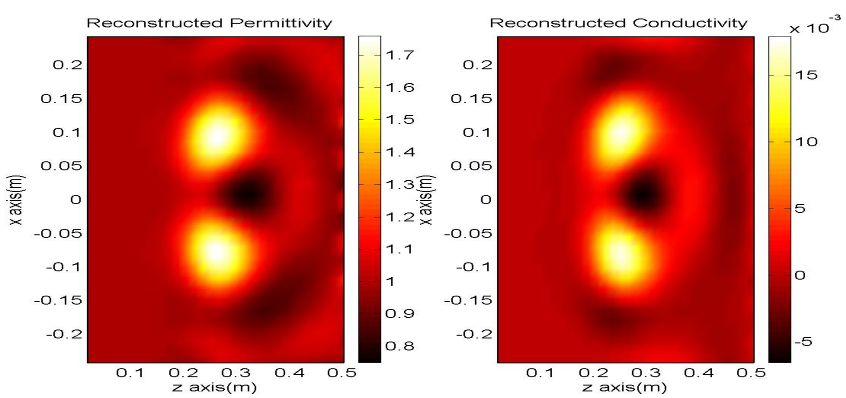

Figure 3: The reconstructed profiles of dielectric objects with the LHM slab when the working frequency is 0.6 GHz.

To view the effect of the LHM slab on the imaging resolution, the dielectric objects are also reconstructed without the LHM slab, as shown in Fig. 4 . Here, 35 transmitters, 35 backward receivers and 35 forward receivers are placed on the measurement lines located at $z = -0.1$ m, 0, and 0.52 m, respectively, to collect scattered data over the range of 2 m. Comparing Figs. 3 and 4, we clearly observe

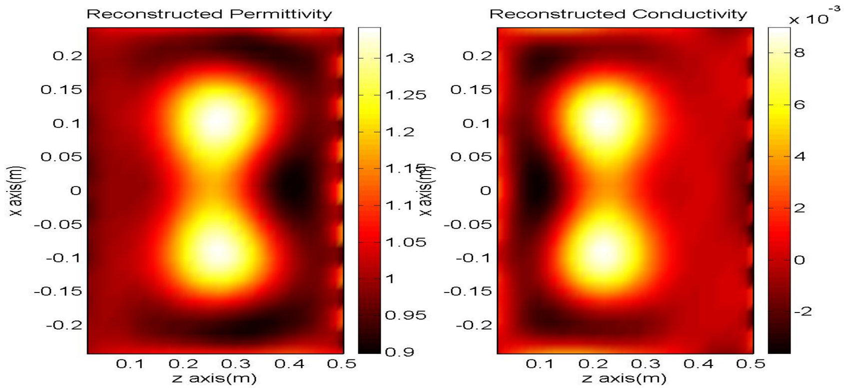

Figure 4: The reconstructed profiles of dielectric objects without the LHM slab when the working frequency is 0.6 GHz.

that a much better resolution is achieved when the LHM slab is involved in the imaging problems. Therefore the LHM slab can play a very important role in the super resolution.

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