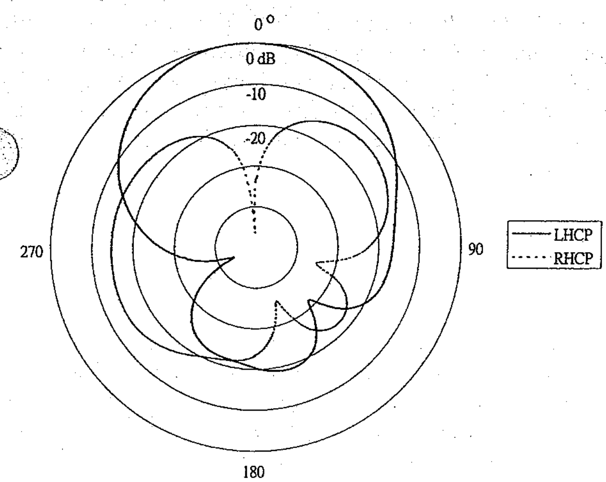

Figure 3 Measured radiation patterns at 1.79 GHz

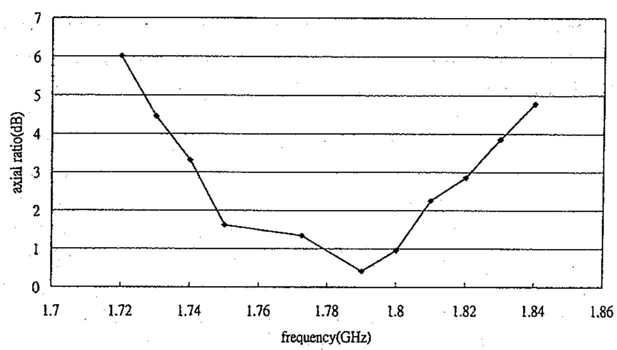

Figure 4 Measured axial ratio versus frequency

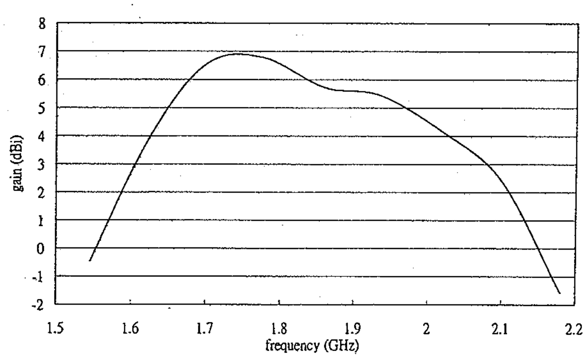

Figure 5 Measured antenna gain versus frequency

can cancel out the feed inductance to enhance the impedance, axial ratio, and gain bandwidth effectively. The use of a cross slot on the circular patch also effectively reduces the physical size of the circular patch.

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APPLICATION AND OPTIMIZATION OF THE PERFECTLY MATCHED LAYER BOUNDARY CONDITION FOR GEOPHYSICAL SIMULATIONS

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ABSTRACT: *The perfectly matched layer (PML) absorbing boundary condition has been used for a wide range of applications since its introduction in 1994. Most of these applications have used the PML in a uniform air-filled zone around a nonair scatterer. This paper describes the application of the PML to a geophysical prospecting problem where the PML is applied in a conductive host material containing the scatterer. The conductivity profile is optimized using parameter estimation.* © 2000 John Wiley & Sons, Inc. Microwave Opt Technol Lett 25: 253–255, 2000.

Key words: *absorbing boundary condition; perfectly matched layer; geophysical simulations; scattering*

INTRODUCTION

The perfectly matched layer (PML) absorbing boundary condition was first introduced by Berenger in 1994 [1], and extended to three dimensions by Katz, Thiele, and Taflove [2]. This boundary condition was shown to provide substantially better absorption of electromagnetic waves than Mur, retarded time, or Liao boundary conditions [1, 2]. The analysis of this boundary condition was initially done for traditional finite-difference time-domain (FDTD) simulations where a scatterer is surrounded by air, and the PML is applied within this external air region. Berenger's formulation of the PML assumes that the host material of the model has infinite resistivity (such as air). Modifications of this formulation have been developed for truncating volumes in which nonair materials that may be conductive, magnetic, anisotropic, dispersive, etc., impinge on the boundary [3–6]. The use of a PML for evanescent waves was examined by DeMoerloose and Stuchly [7]. These PML absorbing boundary conditions can be used to effectively eliminate spurious reflections from the outer surface of the computational mesh.

The effectiveness of the PML technique relies upon an appropriate choice of stretching factor profiles (or conductivity profiles) within the absorbing boundary layer. Suitable profiles depend on the frequency of interest and resolution of the FDTD grid, and can be found by either trial and error or different types of mapping methods as in [8]. A more rigorous method of finding the optimized conductivity profile for PMLs was applied by Lazzi and Gandhi using Newton's nonlinear optimization technique [9]. This method was done for the standard Berenger PML in air for a single frequency.

This paper describes the application and optimization of the PML formulation developed by Chen, Chew, and Oristaglio [3] and Chew and Weedon [4] for a geophysical simulation of a cross-borehole method to delineate a conductive ore deposit. The PML is suitable for use in nonair material and pulsed (multifrequency) sources, and the optimization is done using parameter estimation.

OPTIMIZATION OF THE PML ABSORBING BOUNDARY CONDITIONS

The PML derivation using "stretched coordinates" [3, 4] is based upon a transformation of Cartesian coordinates:

$$\{x, y, z\} \rightarrow \{xs_x, ys_y, zs_z\} \tag{1}$$

where the "coordinate stretching factors" s_x, s_y, and s_z are complex numbers. A stretching factor s is defined as

$$s(p) = \frac{\beta(p)}{\omega_c \varepsilon} + i\frac{\alpha(p)}{\omega\varepsilon} \tag{2}$$

where ω_c is the source center frequency, and p corresponds to the elements of the Cartesian basis x, y, or z. The functions $\alpha(p)$ and $\beta(p)$ control the rate of attenuation within the PML in the direction p. Choosing $\alpha(p) = 0$ and $\beta(p) = \omega_c \varepsilon$ reduces the PML equations to Maxwell's equations, so that the rate of attenuation within the medium is controlled by its physical properties. In resistive media, this rate of attenuation may be too small to guarantee that all EM energy is dissipated before reaching the outer edges of the computational domain. Greater rates of attenuation can be attained by choosing larger values of α and β. However, an attenuation rate that is too large gives rise to spurious numerical reflections. A compromise must be reached between insufficient attenuation, which causes EM waves to reach the outer boundary of the mesh and reflect back into the region of interest, and excessive attenuation, which causes spurious reflections to occur at interfaces within the PML.

The performance of the PML absorber can be optimized by the application of parameter estimation. Let the exact solution to a given EM propagation problem be given by $\mathbf{d}^o$, which is observed data to be fitted by a set of predicted data $\mathbf{d}^p$ produced by the FDTD numerical model. Now, define A as the forward modeling operator that maps a set of PML coefficients $\mathbf{m}$ onto a set of predicted data $\mathbf{d}^p$:

$$\mathbf{d}^p = A(\mathbf{m}). \tag{3}$$

Having fixed the physical parameters of the model, the PML coordinate stretching factors define the set of free model parameters. The error due to numerical reflections from the PML is equal to the misfit between the observed data $\mathbf{d}^o$ and the predicted data $\mathbf{d}^p$ that correspond to the model parameters $\mathbf{m}$. The goal is to minimize this misfit. Simply minimizing this misfit will, unfortunately, lead to PML profiles that are wildly varying between the layers, and although this may theoretically lead to an optimal PML, these rough profiles tend to be highly problematic and sensitive to numerical errors. A better PML is obtained by requiring the variation between the layers to be smooth. There are several ways of doing this. For this paper, the PML parameters were optimized while model $\mathbf{m}$ is as close as possible to some *a priori* model $\mathbf{m}_{apr}$. In this case, $\mathbf{m}_{apr}$ is simply our initial model, chosen to be a "good" model found by trial and error or past experience. Thus, we seek to minimize the regularized misfit functional:

$$\begin{aligned}\phi(m^p) &= \|d^p - d^o\|^2 + \kappa\|m - m_{apr}\|^2 \\ &= \|A(m^p) - d^o\|^2 + \kappa\|m - m_{apr}\|^2.\end{aligned} \tag{4}$$

Here, κ is a regularization coefficient, which controls the degree to which minimization of the misfit function is traded for minimization of variation in the model parameters from the *a priori* model. It is more important to obtain a low value of the misfit functional for a given background medium than it is to maintain a small degree of variation from the *a priori* coordinate stretching coefficients. Therefore, we can permit κ to become small as we approach the desired minimum misfit.

This problem can be solved using parameter estimation techniques. A parameter estimation technique implemented by Portniaguine and Zhdanov [10] was applied in this case. This method uses a regularized Newton method, with Frechet derivatives calculated by finite differencing. In practice, the inversion for PML profiles is highly nonlinear, and therefore difficult to solve using this technique. Attempts to solve the inverse problem for independently varying coordinate stretching factors failed because the forward modeling algorithm is unstable with respect to perturbations in these parameters, resulting in the Frechet derivatives being undefined. This problem was dealt with by parameterizing the real and imaginary parts of the PML coordinate stretching factor profiles in terms of simple functions, such as sines, which are particularly desirable because of their smoothness. For minimal reflection, the PML equations should match Maxwell's equations at the interior boundary of the layer, and the stretching factors may increase toward the outer boundary. In practice, it was necessary to introduce a dc offset in the stretching factor profiles to account for discretization of the PML. The stretching parameters to be optimized are therefore given by

$$\alpha(n) = \frac{a_\alpha}{2}\left[1 + \sin\left(\frac{n\pi}{\mathrm{NPML}} - \frac{\pi}{2}\right)\right] + b_\alpha \tag{5}$$

and

$$\beta(n) = \omega_c\varepsilon + \frac{a_\beta}{2}\left[1 + \sin\left(\frac{n\pi}{\mathrm{NPML}} - \frac{\pi}{2}\right)\right] + b_\beta \tag{6}$$

where NPML is the number of cells in the PML, and n is the number of cells between the given node and the interior boundary of the PML. The variables a_α, a_β, and b_β are the new model parameters to be optimized.

A one-dimensional EM wave propagation problem was used as the forward modeling operator A which can be computed simply and rapidly. The PML coordinate stretching factors estimated using such a model may be applied to a three-dimensional modeling problem with similar physical and numerical parameters.

A standard one-dimensional FDTD code was used for the optimization, and a plane-wave vertical magnetic field pulse was introduced by forcing the vertical magnetic field at one point in an FDTD mesh, representing a plane perpendicular

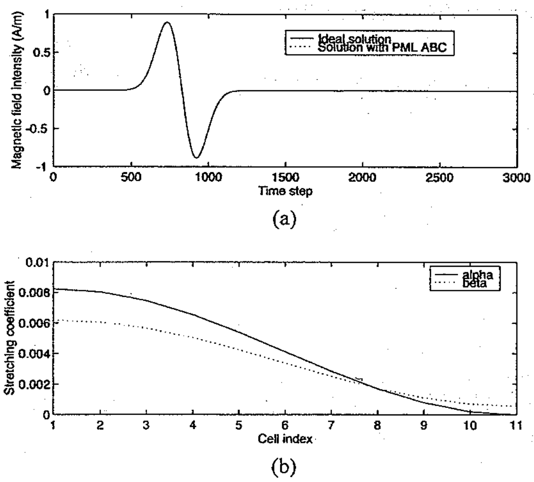

Figure 1 Optimized PML profile results. (a) Comparison of the ideal reflection-free solution and the solution showing (negligible) reflections from the PML. (b) Optimal profiles for alpha and beta

to the line. The magnetic field in this plane is given by

$$H_z(t) = -20(t - t_0)\sqrt{\frac{e}{20}}\, e^{-0(t-t_0)^2} \qquad (7)$$

where $\theta = \omega_c^2/2$ and the center frequency is 1 MHz. The relative electrical permittivity $\varepsilon_r = 10$, the magnetic permeability $\mu = \mu_0$, and the conductivity $\sigma = 0.0001$ S/m, which are typical parameters of a host rock.

To obtain an ideal, reflection-free set of data, the effect of a boundless host medium was simulated by extending the finite-difference mesh a sufficient distance from the transmitter–receiver pair, such that no numerical reflections from the mesh boundaries were observed at the receiver during the time interval of interest. This model provided the ideal, reflection-free set of observed data $\mathbf{d}^o$. The transmitter–receiver pair was then moved to a point near the interface between the PML and the interior region of the mesh. The model data generated in this configuration provided the predicted data $\mathbf{d}^p$ which were to be fit to the observed data in a least squares sense by adjusting the PML coordinate stretching factor profile.

The parameter estimation program PAREST [10] was used to minimize the misfit functional given in (4) by adjusting the parameters a_α, b_α, a_β, and b_β in (5) and (6). The optimized stretching coefficients are shown in Figure 1(b). The performance of the optimized PML was tested by comparing the ideal reflection-free fields with the fields obtained using the PML. As shown in Figure 1(a), the results are excellent.

CONCLUSION

The use of parameter estimation techniques for optimizing PML boundary conditions was examined. It was found that the solution of this problem is highly non-linear, and provided spurious results unless some *a priori* model was used to smooth the data. This was done using a sinusoidal profile for the PML, and optimized results provided an excellent PML for a pulsed source in a nonair interface.

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ON PLANE-WAVE SCATTERING FROM AN AZIMUTHALLY PERIODIC CYLINDRICAL STRUCTURE

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ABSTRACT: *Scattering from an azimuthally periodic cylindrical structure is carried out with the objective of minimizing, with a systematic strategy, the number of times required to analyze the basic periodic sector, and the number of Hankel functions needed for describing the scattered field. A hybrid FEM / BEM has been implemented for validation.* © 2000 John Wiley & Sons, Inc. Microwave Opt Technol Lett 25: 255–257, 2000.

Key words: *electromagnetic scattering; periodic structures; finite-element method*

I. INTRODUCTION

Recently, several papers have dealt with the scattering from cylindrical structures that show an azimuthal periodicity [1–6]. Some of them introduce the periodicity of the structure by expanding the scattering field in terms of an orthonormal set of Floquet harmonics [1–4]. This allows one to deal with a basic sector (or period) of the structure only. However, the basic sector has to be analyzed for each of the infinite cylindrical harmonics in which the incident wave can be decomposed. It is now our intention to verify that it is sufficient to analyze the basic sector only a number of times