Radio Wave Propagation Inside Two Adjacent Partially Dielectric Loaded Troughs †

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ABSTRACT

An electromagnetic wave propagation inside two adjacent rectangular troughs, which are partially filled by dielectric materials, is analyzed in this paper, by using the Kobayashi Potential method (KP method). The structure may be considered as a simple canonical model of the indoor structures with the window interfaces between outdoor and indoor environments. So as compared with the single trough's solution, one can extract and evaluate the multiple diffraction effects from the two troughs' solution derived here.

INTRODUCTION

With the diffusion of personal communication services, it has been one of the most important topics to investigate how radio waves propagate in urban complex, because the strange radio wave behavior may contribute to the annoying interference or the undesirable fading effects [1]. Also, for indoor structures with low power systems [2],[3], it has been reported that office furnitures like desks, cabinets, shelves, and human bodies may become the obstacles of indoor wireless LAN systems. On the other hand, there have been few researches for understanding wave propagation mechanism through outdoor/indoor interfaces like windows when the wave impinges on the interfaces from outdoor to indoor environments.

In order to design appropriate wireless communication systems, ray tracing techniques based on Geometrical Theory of Diffraction (GTD) have been applied to the simulation of both outdoor and indoor environments, because they provide easy wave propagation prediction for each system and high computer efficiency. However, such ray based techniques may not be suitable to analyze dielectric objects with edges. One may be able to treat the reflection effect from the surface with the aid of the impedance boundary conditions, but not for the transmitted field. In addition, the multiple diffraction interactions between adjacent windows may also be troublesome for such high frequency techniques. Therefore, the alternative methods may be required for the propagation analyses through the outdoor/indoor interfaces.

To develop the simulation technique for modeling outdoor/indoor interfaces, an electromagnetic wave propagation inside two adjacent partially dielectric loaded rectangular troughs is analyzed in this paper, by using the Kobayashi Potential method (KP method) [4]-[6]. The KP method is a kind of eigen-function expansion methods for mixed boundary value problems utilizing the characteristics of Weber-Schafheitlin type integrals [4]. The contribution of the multiple diffraction effect will be discussed by the numerical calculations of the field distributions at the vicinity of the dielectric

†This research was partially supported by a Scientic Research Grant-In-Aid (13650425, 2001) from the Ministry of Education, Culture, Sports, Science and Technology, Japan.

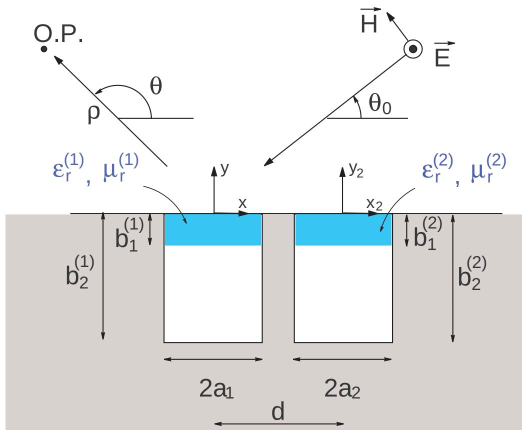

Figure 1: Geometry of the problem

interfaces (windows). Here the time harmonic factor $e^{-i\omega t}$ is assumed and suppressed throughout the context.

FORMULATION

As shown in Figure 1, two rectangular troughs of width $2a_j$ and depth $b_2^{(j)}$ with $j = 1, 2$ are set on a ground plane, where each trough is separated by a distance d. They are also partially loaded by complex materials with relative permittivity $\epsilon_r^{(j)}$ and relative permeability $\mu_r^{(j)}$. Let us consider the problem for the case that E polarized plane wave:

$$\phi^i \, (= E_z^i) = e^{-ik_0(x\cos\theta_0 + y\sin\theta_0)} \tag{1}$$

impinges on the troughs, where k_0 is free space wavenumber. For convenience, the entire region is now divided into three regions, i.e., semi-infinite half space ($y > 0$) is region I, the cavity space within $-b_2^{(1)} < y < 0$, $|x| < a_1$ is region II-(1), and the space in $-b_2^{(2)} < y_2 < 0$, $|x_2| < a_2$ is region II-(2), where $(x_2, y_2)(= (x - d, y))$ is a supplementary coordinate for making the formulation easier. In region I, the total field $\phi^t(= E_z^t)$ may be considered as $\phi^t = \phi^i + \phi^r + \phi^{(1)} + \phi^{(2)}$, where ϕ^i is the incident field, ϕ^r is the reflected field from the ground plane, and $\phi^{(j)}$ is the scattering field contribution due to the existence of each trough, respectively. According to the procedure of the KP method [4]-[6], $\phi^{(j)}$ may be expressed as

$$\phi^{(j)} = \sum_{m=0}^{\infty} \int_0^{\infty} \left\{ A_m^{(j)} \frac{J_{2m+1}(\xi)}{\xi} \cos\xi u_j + B_m^{(j)} \frac{J_{2m+2}(\xi)}{\xi} \sin\xi u_j \right\} e^{-\sqrt{\xi^2 - \kappa_{j0}^2} v_j} d\xi, \tag{2}$$

where $A_m^{(j)}$ and $B_m^{(j)}$ are the unknown expansion coefficients, and normalization with respect to each half aperture width a_j ($x = a_1 u_1, x_2 = a_2 u_2, y = a_1 v_1, y_2 = a_2 v_2, k_0 a_j = \kappa_{j0}$) is executed. With the discontinuity features of the Weber-Schafheitlin type integrals, $\phi^{(1)}$ and $\phi^{(2)}$ must be reduced to zeros on $|x| > a_1, y = 0$ and $|x_2| > a_2, y_2 = 0$, respectively. Thus, it can be confirmed that the total field ϕ^t in region I automatically satisfy the required boundary condition on the conducting ground plane [6].

While, in region II-(1) and II-(2), the fields $\phi_{II}^{(j)}$ may be represented as

$$\phi_{II}^{(j)} = \sum_{n=1}^{\infty} E_n^{(j)} \sin\{\frac{n\pi}{2}(1 - u_j)\} \cdot \left[e^{-ih_n^{(j)} a_j v_j} - R_n^{(j)} e^{+ih_n^{(j)} a_j v_j} \right], \quad (-b_1^{(j)} < y \, (or \ y_2) < 0) \tag{3}$$

$$\phi_{II}^{(j)} = \sum_{n=1}^{\infty} E_n^{(j)} \sin\{\frac{n\pi}{2}(1-u_j)\} \cdot \sin\{h_{n0}^{(j)}(y+b_2^{(j)})\} \cdot T_n^{(j)}, \quad (-b_2^{(j)} < y \,(or\ y_2) < -b_1^{(j)}) \tag{4}$$

where $E_n^{(j)}$ is the excitation coefficient inside each trough, $h_n^{(j)} (= \{\epsilon_r^{(j)}\mu_r^{(j)}\kappa_{j\,0}^2 - (n\pi/2)^2\}^{1/2}/a_j)$ and $h_{n0}^{(j)} (= \{\kappa_{j\,0}^2 - (n\pi/2)^2\}^{1/2}/a_j)$ are the propagation constants with respect to $y\,($ or $y_2)$ axis in the loaded material and free space, respectively. Here,

$$R_n^{(j)} = \frac{\mu_r^{(j)} h_{n0}^{(j)} \cos\{h_{n0}^{(j)}(-b_1^{(j)}+b_2^{(j)})\} + i h_n^{(j)} \sin\{h_{n0}^{(j)}(-b_1^{(j)}+b_2^{(j)})\}}{\mu_r^{(j)} h_{n0}^{(j)} \cos\{h_{n0}^{(j)}(-b_1^{(j)}+b_2^{(j)})\} - i h_n^{(j)} \sin\{h_{n0}^{(j)}(-b_1^{(j)}+b_2^{(j)})\}} \cdot e^{i2h_n^{(j)}b_1^{(j)}}, \tag{5}$$

$$T_n^{(j)} = \frac{-i2\mu_r^{(j)} h_n}{\mu_r^{(j)} h_{n0}^{(j)} \cos\{h_{n0}^{(j)}(-b_1^{(j)}+b_2^{(j)})\} - i h_n^{(j)} \sin\{h_{n0}^{(j)}(-b_1^{(j)}+b_2^{(j)})\}} \cdot e^{-ih_n^{(j)}b_1^{(j)}} \tag{6}$$

Thus, the problem may be reduced to determine the coefficients $A_m^{(j)}, B_m^{(j)}$ and $E_n^{(j)}$ included in Eqs.(2), (3) and (4). Taking into account the continuity conditions of the tangential field components at the apertures, one can obtain the simultaneous equations as

$$\sum_{m=0}^{\infty} A_m^{(1)}\{K^{(1)}(2q+1,2m+1) + KN^{(1)}(2q+1,2m+1)\} = -2iJ_{2q+1}(\kappa_{10}\cos\theta_0)\frac{\sin\theta_0}{\cos\theta_0}$$
$$+ \sum_{m=0}^{\infty}\{-A_m^{(2)}KC^{(2)}(2q+1,2m+1;\frac{a_1}{a_2},\frac{d}{a_2}) + B_m^{(2)}KS^{(2)}(2q+1,2m+2;\frac{a_1}{a_2},\frac{d}{a_2})\}, \tag{7}$$

$$\sum_{m=0}^{\infty} B_m^{(1)}\{K^{(1)}(2q+2,2m+2) + KN^{(1)}(2q+2,2m+2)\} = -2J_{2q+2}(\kappa_{10}\cos\theta_0)\frac{\sin\theta_0}{\cos\theta_0}$$
$$+ \sum_{m=0}^{\infty}\{-A_m^{(2)}KS^{(2)}(2q+2,2m+1;\frac{a_1}{a_2},\frac{d}{a_2}) - B_m^{(2)}KC^{(2)}(2q+2,2m+2;\frac{a_1}{a_2},\frac{d}{a_2})\}, \tag{8}$$

$$\sum_{m=0}^{\infty} A_m^{(2)}\{K^{(2)}(2q+1,2m+1) + KN^{(2)}(2q+1,2m+1)\} = -2iJ_{2q+1}(\kappa_{20}\cos\theta_0)\frac{\sin\theta_0}{\cos\theta_0}\, e^{-ik_0 d\cos\theta_0}$$
$$+ \sum_{m=0}^{\infty}\{-A_m^{(1)}KC^{(1)}(2q+1,2m+1;\frac{a_2}{a_1},\frac{d}{a_1}) - B_m^{(1)}KS^{(1)}(2q+1,2m+2;\frac{a_2}{a_1},\frac{d}{a_1})\}, \tag{9}$$

$$\sum_{m=0}^{\infty} B_m^{(2)}\{K^{(2)}(2q+2,2m+2) + KN^{(2)}(2q+2,2m+2)\} = -2J_{2q+2}(\kappa_{20}\cos\theta_0)\frac{\sin\theta_0}{\cos\theta_0}\, e^{-ik_0 d\cos\theta_0}$$
$$+ \sum_{m=0}^{\infty}\{+A_m^{(1)}KS^{(1)}(2q+2,2m+1;\frac{a_2}{a_1},\frac{d}{a_1}) - B_m^{(2)}KC^{(1)}(2q+2,2m+2;\frac{a_2}{a_1},\frac{d}{a_1})\}, \tag{10}$$

where

$$K^{(j)}(\alpha,\beta) = \int_0^{\infty} \frac{\sqrt{\xi^2-\kappa_{j0}^2}}{\xi^2} J_\alpha(\xi)J_\beta(\xi)d\xi, \tag{11}$$

$$KN^{(j)}(2q+1,2m+1) = -\pi \sum_{n=0}^{\infty} \frac{J_{2q+1}(\frac{2n+1}{2}\pi)J_{2m+1}(\frac{2n+1}{2}\pi)\, ih_{2n+1}^{(j)}a_j}{(\frac{2n+1}{2}\pi)^2}\, \frac{1+R_{2n+1}^{(j)}}{1-R_{2n+1}^{(j)}}, \tag{12}$$

$$KN^{(j)}(2q+2,2m+2) = -\pi \sum_{n=0}^{\infty} \frac{J_{2q+2}((n+1)\pi)J_{2m+2}((n+1)\pi)\, ih_{2n+2}^{(j)}a_j}{\{(n+1)\pi\}^2}\, \frac{1+R_{2n+2}^{(j)}}{1-R_{2n+2}^{(j)}}, \tag{13}$$

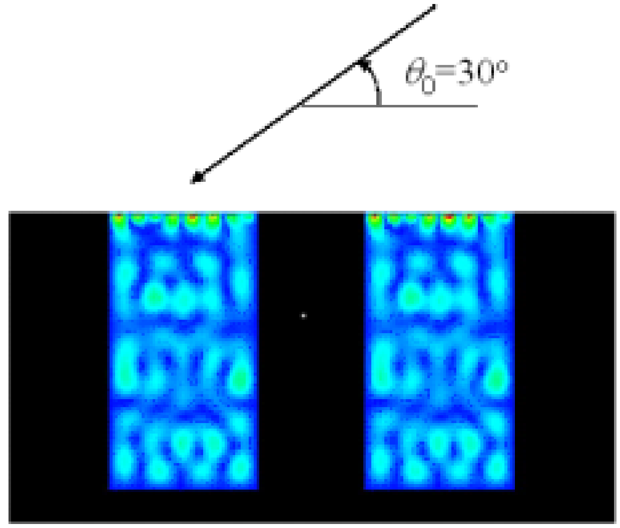

Figure 2: Field distribution inside the two troughs: f=1.0GHz, $\theta_0 = 30^o$, $2a$=80cm, b_1=2cm, b_2=150cm, $d-2a$=20cm, $\epsilon_r^{(1)} = \epsilon_r^{(2)}$=6.9+i0.1 $\mu_r^{(1)} = \mu_r^{(2)}$=1.0.

$$KC^{(j)}(\alpha,\beta;P,Q) = \int_0^\infty \frac{\sqrt{\xi^2-\kappa_{j0}^2}}{\xi^2} J_\alpha(P\xi)J_\beta(\xi)\cdot\cos Q\xi\,d\xi, \tag{14}$$

$$KS^{(j)}(\alpha,\beta;P,Q) = \int_0^\infty \frac{\sqrt{\xi^2-\kappa_{j0}^2}}{\xi^2} J_\alpha(P\xi)J_\beta(\xi)\cdot\sin Q\xi\,d\xi. \tag{15}$$

Comparing these simultaneous deterministic equations (7) to (10) with ones for single trough analysis, the second and third terms of the right-hand sides may be considered as the coupling contribution between troughs [5],[6].

NUMERICAL RESULTS

Using the above formulation, numerical calculation of the field distribution inside the troughs has been performed. Though the detail data is omitted here, we have already checked the accuracy of the derived solution by comparing with the other rigorous reference solution for empty case.

Figure 2 shows the field distribution inside the partially material loaded troughs. Here the two troughs with the same width $2a\,(=2a_1=2a_2)$ and depth $b_2\,(=b_2^{(1)}=b_2^{(2)})$ are considered, and the materials with same thickness $b_1\,(=b_1^{(1)}=b_1^{(2)})$ are loaded at the apertures. It is observed from the numerical result that the electric field intensity extremely decreases by passing through the loaded material. Also, it seems that the contribution of the multiple scattering effect is very small for this polarization.

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