Research Article

A Comparison Study for Investigation of Diffracted Waves between Parallel Edges and Edges with Arbitrary Angle

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Estimation of the scattering of electromagnetic waves by buildings and other obstacles is very important for wireless communications. In our previous work, we have examined the diffracted fields by two horizontal edges which make an arbitrary angle. In this paper, we compare the diffracted fields between parallel edges and edges with arbitrary angle. The numerical calculation results show that when the angle between two edges increases, relatively strong orthogonal polarized wave components appear, but the principal components are almost the same as the incident wave.

1. Introduction

Electromagnetic waves can be scattered by edges of the buildings in urban areas or edges of the mountain (ridges) for long communication. Thus, the communication quality deteriorates. Therefore, it is important to estimate propagation path from the viewpoint of the effective utilization of the radio wave resources. However, the prediction of the propagation path is not easy.

Until now, there are many research works dealing with estimation of the radio wave propagation path in the urban areas [1, 2]. These papers mainly analyzed and examined the propagation path of radio waves when in the urban area there are many buildings. For the case when the waves exceed building roof, Zhang analyzed propagating radio wave over a large number of buildings [3].

In our previous works, we have examined the diffracted fields by two horizontal edges which make an arbitrary angle [4, 5]. But it is almost impossible to find diffraction points on these edges analytically [6], so we used a method which can find the diffraction points by repetition process [5]. However, it should be noted that edges are not always horizontal. Thus, it is necessary to examine the diffracted field by edges which change in both horizontal and vertical directions [7]. We

also discussed the fields diffracted by wedges and showed that wedge shapes, materials, and incident polarization do not have significant effect on diffracted fields except near the wedge surfaces [8].

In this paper, first we survey the double diffraction by two edges which make an arbitrary angle. Then, we refer to coordinate transformation between a total coordinate system and an edge-fixed one and explain the method for finding the diffraction points on two edges with an arbitrary angle which change in both horizontal and vertical directions. For the analysis of diffracted fields, we used GTD (geometrical theory of diffraction) [9, 10]. We make the analysis by including the slope diffraction considering Holm's method [11, 12]. The numerical calculations are carried out on perfect conductor. The results show that when the angle between two edges increases, relatively strong orthogonal polarized wave components appear, but the principal components are the same as the incident wave.

This paper is organized as follows. In Section 2, we present diffraction by two edges containing coordinate transformation and the method of finding the diffraction points and introduce the diffraction by two edges. In Section 3, we present the numerical examples. Finally, some conclusions are given in Section 4.

FIGURE 1: Diffraction by two edges.

2. Diffraction by Two Edges

2.1. Aspect of Double Diffraction. In Figure 1(d), the aspect of double diffraction by edges 1 and 2 is shown. We express edge i ($i = 1, 2$) by e_i , which makes an arbitrary angle in horizontal and vertical planes. The wave from a source $S_0(x_S, y_S, z_S)$ is diffracted twice, at point Q_1 on e_1 and at point Q_2 on e_2 , and it reaches an observation point $P_0(x_P, y_P, z_P)$. We use three coordinate systems #0, #1 and #2, and the origins of #1 and #2 are, respectively, at (a_1, b_1, c_1) and (a_2, b_2, c_2) of coordinate system #0. The edges e_1 and e_2 agree with y_1 -axis and y_2 -axis of coordinate systems #1 and #2. It should be noted that the subscript i in $(x, y, z)_i$ means the coordinate system # i , but the subscript 0 of #0 is omitted. Figure 1(a) shows the front view of two waxes. Figures 1(b) and 1(c) show the top view and side view of Figure 1(d). The wedges are supposed to rotated by angle ψ_i ($i = 1, 2$) counterclockwise in a horizontal plane as shown in Figure 1(b) and inclined by angle τ_i in a vertical plane in Figure 1(c) (in Figure 1, ψ_2 and τ_2 are drawn as $\psi_2 < 0$ and $\tau_2 < 0$).

2.2. Coordinate Transformation. It is difficult to analyze the diffracted field by edges with an arbitrary angle. But the analysis becomes easier by using coordinate transformation as described below.

Let us consider Figure 1 to explain the coordinate transformation. The origin of coordinate system # i ($i = 1, 2$) is put at (a_i, b_i, c_i) of coordinate system #0, and # i is supposed to be rotated by ψ_i counterclockwise around z_i -axis (# i z -axis) as shown in Figure 1(b). Furthermore, the z_i -axis is inclined by τ_i around x_i -axis (Figure 1(c)). A point $(x_i, y_i, z_i)_i$ on # i

is obtained from a point (x, y, z) on #0 by the following equation:

$$\begin{pmatrix} x_i \\ y_i \\ z_i \end{pmatrix} = T_{i0} \begin{pmatrix} x - a_i \\ y - b_i \\ z - c_i \end{pmatrix}, \quad (1)$$

$$T_{i0} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \tau_i & \sin \tau_i \\ 0 & -\sin \tau_i & \cos \tau_i \end{pmatrix} \begin{pmatrix} \cos \psi_i & \sin \psi_i & 0 \\ -\sin \psi_i & \cos \psi_i & 0 \\ 0 & 0 & 1 \end{pmatrix}.$$

On the other hand, a point (x, y, z) on #0 is obtained from a point $(x_i, y_i, z_i)_i$ on # i as follows:

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = T_{0i} \begin{pmatrix} x_i \\ y_i \\ z_i \end{pmatrix} + \begin{pmatrix} a_i \\ b_i \\ c_i \end{pmatrix}, \quad (2)$$

$$T_{0i} = \begin{pmatrix} \cos \psi_i & -\sin \psi_i & 0 \\ \sin \psi_i & \cos \psi_i & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \tau_i & -\sin \tau_i \\ 0 & \sin \tau_i & \cos \tau_i \end{pmatrix}.$$

In addition, the relationship between a vector $\mathbf{A} = \hat{\mathbf{x}}A_x + \hat{\mathbf{y}}A_y + \hat{\mathbf{z}}A_z$ on #0 and a vector $\mathbf{A}_i = \hat{\mathbf{x}}_iA_{ix} + \hat{\mathbf{y}}_iA_{iy} + \hat{\mathbf{z}}_iA_{iz}$ on # i is shown as follows:

$$\begin{aligned} \mathbf{A}_i &= T_{i0}\mathbf{A}, \\ \mathbf{A} &= T_{0i}\mathbf{A}_i. \end{aligned} \quad (3)$$

FIGURE 2: Aspect of diffraction by an edge e_i .

2.3. Diffracted Field by Edge e_i . Firstly, we would consider a diffraction by an edge e_i ($i = 1, 2$) of a wedge i . The aspect of diffraction at Q_i on an edge e_i on the coordinate system $\#i$ is shown in Figure 2. The wedge which constitutes e_i has the external angle $n_i\pi$ and it consists of 0-plane and n -plane which are in the angle of θ_{i0} , θ_{in} from the z_i ($z_i < 0$) axis. The source point S_0 , the observation point P_0 , and a unit vector of the current at S_0 are expressed as $S_0(x_{iS}, y_{iS}, z_{iS})_i$, $P_0(x_{iP}, y_{iP}, z_{iP})_i$, and $\hat{\mathbf{i}}_i$ of coordinate system $\#i$. The electromagnetic wave emitted from the source S_0 is diffracted at point Q_i on e_i and reaches the observation point P_0 . According to GTD, as the angle α_{iS} between the incident path S_0Q_i and e_i (y_i axis) is equal to the angle α_{iP} between the path Q_iP_0 after the diffraction and e_i [9], the point $Q_i(0, y_{Q_i}, 0)_i$ is easily obtained as follows:

$$y_{Q_i} = \frac{\rho_{P_0i} y_{iS} + \rho_{S_0i} y_{iP}}{\rho_{P_0i} + \rho_{S_0i}}, \quad (4)$$

where ρ_{P_0i} and ρ_{S_0i} are the distances from the e_i to the points P_0 and S_0 , respectively. Thus, the distances, the angles, the unit vectors $\hat{\mathbf{r}}_{Si}$ and $\hat{\mathbf{a}}_{iS}$, and so on in Figure 2 can be calculated.

Therefore, the single diffracted field $\mathbf{E}_i^{d1}$ at point Q_i on the e_i is obtained by the following equations [10–12]:

$$\mathbf{E}_i^{d1} = E_0 \frac{e^{-jk r_{SiP}}}{r_{SiP}} \sqrt{\frac{r_{SiP}}{r_{Si} r_{iP}}} (\hat{\mathbf{r}}_{Si} \times \hat{\mathbf{i}}_i \times \hat{\mathbf{r}}_{iP}) \cdot \bar{\mathbf{D}}_{SiP}, \quad (5)$$

where E_0 is a constant and k is the wave number. The r_{Si} and r_{iP} are the distances between S_0 and Q_i and between Q_i and P_0 , respectively, and $r_{SiP} = r_{Si} + r_{iP}$. The $\hat{\mathbf{r}}_{Si}$ and $\hat{\mathbf{i}}_i$ are unit vectors of r_{Si} and the current at the source S_0 . The $\bar{\mathbf{D}}_{SiP}$ is the dyadic diffraction coefficient of the diffracted wave from S_0 to Q_i until it reaches P_0 . The diffracted field $\mathbf{E}_i^{d1}$ in (5) described by $\#i$ is easily transformed to $\mathbf{E}^{d1}$ on $\#0$ using (3).

2.4. Diffraction Points Q_1 and Q_2 on Two Edges. When edges make arbitrary angle in a plane or they are parallel in different heights, the diffraction points can be found easily [5]. But, when they make arbitrary angle in the space, it is impossible to find the diffraction points analytically. So, we use the following method to find the diffraction points [7] as shown in Figure 3.

- (1) Let us assume $Q_1(0, y_{Q1}, 0)_1$, which is the diffraction point on e_1 as given in preceding subsection, to be a first diffraction point $Q_1^{(1)}$ (subscript 1 means diffraction point on e_1 and superscript (1) means 1st step for finding the last diffraction point).
- (2) The temporary diffraction point $Q_2^{(1)}$ on the edge e_2 is given as follows (see Figure 3(a)).
 - (a) A plane A_1 can be defined containing the point $Q_1^{(1)}$ and e_2 .
 - (b) S_0 is rotated around e_1 with a constant distance of ρ_{S01} as shown in Figure 2; then S_0 reaches a point $S_1(x_{S12}, y_{S12}, z_{S12})_2$ on the plane A_1 .
 - (c) Then using the distance from S_1 to e_2 (ρ_{S12}) and the distance from P_0 to e_2 (ρ_{P02}), the first temporary diffraction point $Q_2^{(1)}(0, y_{Q21}, 0)_2$ on e_2 is given by

$$y_{Q21} = \frac{\rho_{P02} y_{S12} + \rho_{S12} y_{P02}}{\rho_{P02} + \rho_{S12}}. \quad (6)$$

- (3) The 2nd temporary diffraction point $Q_1^{(2)}$ on the edge e_1 is given as follows.
 - (a) A plane A_2 can be constructed using the point $Q_2^{(1)}$ and e_1 .
 - (b) P_0 is rotated around C_{P2} with the length ρ_{P02} shown in Figure 3(a), and then P_0 reaches a point $P_2(x_{P21}, y_{P21}, z_{P21})_1$ on the plane A_2 as shown in Figure 3(b).
 - (c) Using ρ_{S01} and ρ_{P21} , the 2nd temporary diffraction point $Q_1^{(2)}(0, y_{Q12}, 0)_1$ on e_1 is given by

$$y_{Q12} = \frac{\rho_{P21} y_{S01} + \rho_{S01} y_{P21}}{\rho_{P21} + \rho_{S01}}. \quad (7)$$

- (4) After that, we repeat the processes (2) and (3) until $\Delta y_{Qin} = |y_{Qin} - y_{Qin-1}|$ ($i = 1, 2; n = 2, 3, \dots$) becomes small enough. Then, we can find the last diffraction points $Q_i (\approx Q_i^{(n)})$.

2.5. Double Diffracted Fields. The double diffracted field $\mathbf{E}^{d2}$ by the point Q_1 on the edge e_1 and the point Q_2 on the edge e_2 is calculated by the following equation considering the slope diffraction [10–12]:

$$\begin{aligned} \mathbf{E}^{d2} &= E_0 \frac{e^{-jk r_{S12P}}}{r_{S12P}} \sqrt{\frac{r_{S12P}}{r_{S1} r_{12} r_{2P}}} (\hat{\mathbf{r}}_{S1} \times \hat{\mathbf{i}}_1 \times \hat{\mathbf{r}}_{S1}) \\ &\cdot \left(\bar{\mathbf{D}}_{S12} \cdot \bar{\mathbf{D}}_{12P} + \frac{j}{kr_{12}} \frac{\partial \bar{\mathbf{D}}_{S12}}{\partial \varphi_{12}} \cdot \frac{\partial \bar{\mathbf{D}}_{12P}}{\partial \varphi_{21}} \right) \\ &= \mathbf{E}_{(1)}^{d2} + \mathbf{E}_{(2)}^{d2}, \end{aligned} \quad (8)$$

FIGURE 3: Diffraction points on edges e_2 and e_1 .

where $r_{S12P} = r_{S1} + r_{12} + r_{2P}$ and φ_{ij} ($i, j = 1, 2$) is the direction angle at the point Q_i toward the point Q_j measured from the 0-plane of the wedge i . The first term in the parenthesis of (8) is the first-order diffraction ($\mathbf{E}_{(1)}^{d2}$) and the second term is the second-order diffraction ($\mathbf{E}_{(2)}^{d2}$; the so-called slope diffraction). When we execute (8), the dyadic diffraction coefficients $\bar{\mathbf{D}}_{S12}$ and $\bar{\mathbf{D}}_{12P}$ are calculated on #1 and #2, respectively. Then, they are transformed to #0 by (3), and the double diffracted fields by e_1 and e_2 are obtained by performing scalar product in (8).

2.6. Total Field. The direct field $\mathbf{E}^{\text{inc}}$ from a source S to the observation point P is obtained as follows:

$$\mathbf{E}^{\text{inc}} = E_0 \frac{e^{-jkr_{SP}}}{r_{SP}} (\hat{\mathbf{r}}_{SP} \times \hat{\mathbf{i}} \times \hat{\mathbf{r}}_{SP}), \quad (9)$$

where r_{SP} is the distance between S and P , and the $\hat{\mathbf{r}}_{SP}$ and $\hat{\mathbf{i}}$ are unit vectors of r_{SP} and the current at S for the coordinate system #0.

The single diffracted field $\mathbf{E}_i^{d1}$ ($i = 1, 2$) by an edge e_i and double diffracted field $\mathbf{E}^{d2}$ by e_1 and e_2 can be obtained by (5) and (8). Considering direct field $\mathbf{E}^{\text{inc}}$ from a source S and the field $\mathbf{E}^{\text{ref}}$ reflected by surfaces of the wedges, the total electric field $\mathbf{E}^t$ at an observation point P is calculated as the sum of these fields:

$$\mathbf{E}^t = \mathbf{E}^{\text{inc}} + \mathbf{E}^{\text{ref}} + \mathbf{E}_1^{d1} + \mathbf{E}_2^{d1} + \mathbf{E}^{d2}. \quad (10)$$

3. Numerical Examples

In this section, we present the numerical calculation. The calculations were carried out for the case where the origin of coordinate system #1 is located at $(a_1, b_1, c_1) = (-50 \text{ m}, 0, h_1)$ of coordinate system #0 and for #2 at $(a_2, b_2, c_2) = (0, 0, h_2)$,

where h_1 and h_2 are the heights of each origin for the coordinate system #0 as shown in Figure 1. The angles of edges with y -axes are ψ_1 , ψ_2 , τ_1 , and τ_2 as shown in Figures 1(b) and 1(c), but we do not consider the field diffracted by an edge formed at an intersection of two wedges and the field reflected by the wedge surfaces and the ground. The source S_0 is at $(x_S, y_S, z_S) = (-100 \text{ m}, 0, h_S)$, the observation point P_0 is at $(x_P, y_P, z_P) = (x_P, 0, 1.5 \text{ m})$, and $E_0 = 1$ in (5), (8), and (9).

When the difference $|\psi_1 - \psi_2|$ or $|\tau_1 - \tau_2|$ becomes large, two edges cross each other near to x -axis or z -axis as shown in Figure 1, and the diffraction points Q_1 and/or Q_2 go out the calculable range. So, we firstly checked the limitation of ψ_1 , ψ_2 and τ_1, τ_2 values. We found that we can nearly calculate diffracted fields when $|\psi_1 - \psi_2| < 90^\circ$ or $|\tau_1 - \tau_2| < 90^\circ$.

In Table 1 the aspect of converging the locations of the diffracted points on two edges e_1 and e_2 is shown. Let the heights of the source and the edges be $h_S = 40 \text{ m}$, $h_1 = 10 \text{ m}$, and $h_2 = 30 \text{ m}$ and let the angles ψ_1 and ψ_2 be 30° and -30° , respectively. Table 1 shows the effect of converging locations of $Q_i(0, y_{Qi}, 0)_i$ ($i = 1, 2$) and the diffraction angles α_i at $x_P = 50 \text{ m}$ and 300 m . In this table, n is the number of repetitions, $\Delta y_{Qin} = |y_{Qin} - y_{Qi(n-1)}|$, and $\Delta \alpha_i = |\alpha_{i1} - \alpha_{i2}|$. According to GTD, the angle α_{i1} between the incident ray and e_i is equal to the angle α_{i2} between e_i and the diffracted ray as shown in Figure 2. Table 1(a) is for horizontal edges ($\tau_1 = \tau_2 = 0^\circ$) and Table 1(b) is for $\tau_1 = 10^\circ$ and $\tau_2 = -10^\circ$. The number of repetitions n has a tendency to increase when ψ_i , τ_i , and/or x_P become large. Although the calculations were carried out for many cases of various angles ψ_i , τ_i and various positions of the # i origins, their results show that the number of repetitions n is relatively small.

In [8], we mentioned that the diffracted fields by wedges are not affected too much by their shapes, material, and incident polarization except near the surfaces of wedges. So, we show the following calculation for the perfectly conducting wedges whose inner angles are zero ($\theta_{i0} = \theta_{in} = 0^\circ$; $i = 1, 2$).

TABLE 1: Relation between Δy_{Qn1} , $\Delta \alpha_i$ ($i = 1, 2$), and n . ($h_1 = 10$ m, $h_2 = 30$ m and $\psi_1 = 30^\circ$, $\psi_2 = -30^\circ$).

(a) $\tau_1 = \tau_2 = 0^\circ$					
x_P [m]	n	Δy_{Qn1} [m]	Δy_{Qn2} [m]	$\Delta \alpha_1$ [deg]	$\Delta \alpha_2$ [deg]
50	1	1.0	—	1.8×10^{-1}	1.2
	2	2.3×10^{-2}	1.6	4.0×10^{-3}	2.7×10^{-2}
	3	4.9×10^{-4}	3.4×10^{-3}	8.7×10^{-5}	5.9×10^{-4}
	4	1.1×10^{-5}	7.3×10^{-5}	1.9×10^{-6}	1.3×10^{-5}
300	1	3.9	—	1.5	5.1
	2	2.0×10^{-1}	1.3	6.7×10^{-2}	2.4×10^{-1}
	3	9.1×10^{-3}	5.6×10^{-2}	3.1×10^{-3}	1.1×10^{-2}
	4	4.2×10^{-4}	2.6×10^{-3}	1.4×10^{-4}	5.1×10^{-4}
	5	1.9×10^{-5}	1.2×10^{-4}	6.4×10^{-6}	2.3×10^{-5}
(b) $\tau_1 = 10^\circ$, $\tau_2 = -10^\circ$					
x_P [m]	n	Δy_{Qn1} [m]	Δy_{Qn2} [m]	$\Delta \alpha_1$ [deg]	$\Delta \alpha_2$ [deg]
50	1	5.6	—	3.3	9.4
	2	7.5×10^{-1}	2.4	3.8×10^{-1}	1.1
	3	8.8×10^{-2}	2.6×10^{-1}	4.4×10^{-2}	1.3×10^{-1}
	4	1.0×10^{-2}	3.0×10^{-2}	5.1×10^{-3}	1.5×10^{-2}
	5	1.2×10^{-3}	3.5×10^{-3}	5.8×10^{-4}	1.7×10^{-3}
	6	1.4×10^{-4}	4.0×10^{-4}	6.8×10^{-5}	2.0×10^{-4}
	7	1.6×10^{-5}	4.6×10^{-5}	7.8×10^{-6}	2.3×10^{-5}
300	1	5.8	—	7.8	11.6
	2	1.6	5.4	1.9	2.8
	3	3.9×10^{-1}	1.2	4.4×10^{-1}	6.8×10^{-1}
	4	9.3×10^{-2}	2.7×10^{-1}	1.1×10^{-1}	1.6×10^{-1}
	5	2.2×10^{-2}	6.4×10^{-2}	2.5×10^{-2}	3.9×10^{-2}
	6	5.3×10^{-3}	1.5×10^{-2}	6.0×10^{-3}	9.3×10^{-3}
	7	1.3×10^{-3}	3.6×10^{-3}	1.4×10^{-3}	2.2×10^{-3}
	8	3.0×10^{-4}	8.7×10^{-4}	3.4×10^{-4}	5.3×10^{-4}
	9	7.2×10^{-5}	2.1×10^{-4}	8.2×10^{-5}	1.3×10^{-4}

Figures 4–6 show the change of the total electric field $|\mathbf{E}^t| = E^t$ and its incident and diffracted components with a distance x_P from a surface of the wedge 2; when the wave is incident to the perfectly conducting wedges whose inner angles are $\theta_{i0} = \theta_{in} = 0^\circ$ ($i = 1, 2$), the heights of source and two edges are $h_S = 40$ m, $h_1 = 10$ m, and $h_2 = 30$ m.

Figure 4 shows the frequency characteristics of the fields when the horizontal polarized wave ($\hat{\mathbf{i}} = \hat{\mathbf{y}}$) is incident and $\phi_1 = \phi_2 = \tau_1 = \tau_2 = 0^\circ$. In this figure, the fields are the total fields (E^t), single diffracted fields ($E_{2,y}^{d1}$) by the e_2 , double diffracted components ($E_{(1),y}^{d2}$), and the slope diffracted components ($E_{(2),y}^{d2}$), where the subscript y means y component. E^{SP} is the direct field from S to P without wedges. At $x_P = 285$ m the direct field E^{inc} appears, so we called the point $x_P = 285.0$ m SB_i (shadow boundary for an incident wave) and the region near to $x_P = 285$ m is called a transition region. When the frequency is doubled, outside the transition

FIGURE 4: Fields diffracted by two wedges and their components for three frequencies (800, 1600, and 3200 MHz) ($\hat{\mathbf{i}} = \hat{\mathbf{y}}$, $h_1 = h_2 = 30$ m, and $\psi_1 = \psi_2 = \tau_1 = \tau_2 = 0^\circ$).

region, $E_{2,y}^{d1}$, $E_{(1),y}^{d2}$, and $E_{(2),y}^{d2}$ are decreased at 3 dB, 6 dB, and 12 dB, respectively [13]. For example, at $x_P = 100$ m $E_{2,y}^{d1}$ is -69.3 dB, -72.4 dB, and -75.4 dB at 800 MHz, 1600 MHz, and 3200 MHz, and $E_{(1),y}^{d2}$ and $E_{(2),y}^{d2}$ are attenuated at 6 dB and 12 dB when frequency is doubled.

Figure 5 shows the fields when the horizontal polarized wave ($\hat{\mathbf{i}} = \hat{\mathbf{y}}$) is incident on the wedges. Figure 5(a) is the case when two edges e_1 and e_2 are parallel ($\psi_1 = \psi_2 = \tau_1 = \tau_2 = 0^\circ$). Only horizontal wave E_y is diffracted and the total field $E^t (= |E_y^i + E_y^{d1} + E_{(1),y}^{d2} + E_{(2),y}^{d2}|)$ increases according to distance x_P because in this case the direct field E^{inc} is added in the range $x_P \geq 285.0$ m.

Figure 5(b) is the case when $\psi_1 = 30^\circ$, $\psi_2 = -30^\circ$, and $\tau_1 = \tau_2 = 0$. As two edges are rotated in horizontal plane, the orthogonal components (E_x , E_z) are generated, and when the angle between two edges increases, relatively strong orthogonal polarized wave components appear to the incident wave. But the horizontal components (E_y^t , $E_{2,y}^{d1}$, $E_{(1),y}^{d2}$, and $E_{(2),y}^{d2}$) change scarcely from Figure 5(a).

Figure 5(c) shows the case that two edges are not rotated in horizontal plane but in vertical plane ($\psi_1 = \psi_2 = 0^\circ$, $\tau_1 = 30^\circ$, and $\tau_2 = -30^\circ$). Comparing Figure 5(c) with Figure 5(b), the orthogonal (z , x) components are different from each other, but the principal components (E^t , E_y^i , and $E_{2,y}^{d1}$) are almost the same as in Figures 5(a) and 5(b).

Figure 6 shows fields for vertically polarized incidence ($\hat{\mathbf{i}} = \hat{\mathbf{z}}$). There are fields diffracted in x and z components.

FIGURE 5: Fields diffracted by two wedges for horizontal polarized incidence.

So, the total field E^t is composed by x and z components. In Figure 6(a) the case when the edges e_1 and e_2 are parallel ($\psi_1 = \psi_2 = \tau_1 = \tau_2 = 0^\circ$) is shown. Comparing Figure 6(a) with Figure 5(a), in Figure 6(a), the x components of the diffracted fields $E_{2,x}^{d1}$, $E_{(1),x}^{d2}$, and $E_{(2),x}^{d2}$ at $x_P = 0$ are not zero because of the boundary condition for conductor. Then, the curve of E^t starts with finite value at $x_P = 0$, but in Figure 5(a) the E^t is zero. But both E^t curves in Figures 5(a) and 6(a) almost agree in the region where x_P is large. Figure 6(b) is the fields when $\psi_1 = 30^\circ$, $\psi_2 = -30^\circ$, and $\tau_1 = \tau_2 = 0^\circ$. The orthogonal components $E_{2,y}^{d1}$, $E_{(1),y}^{d2}$, and $E_{(2),y}^{d2}$ are generated, but the principal components (E^t , E^i , $E_{2,z}^{d1}$, and $E_{2,x}^{d1}$) change a little bit. Figure 6(c) shows the case for $\psi_1 = \psi_2 = 0^\circ$, $\tau_1 = 30^\circ$,

and $\tau_2 = -30^\circ$. The y component of single diffracted wave $E_{2,y}^{d1}$ is zero, and the double diffracted components ($E_{(1),z}^{d2}$, $E_{(1),x}^{d2}$, etc.) are different from those of Figure 6(b), but the principal components are almost the same as in Figures 6(a) and 6(b).

4. Conclusions

In this paper, we considered the diffracted fields by two edges, parallel edges and edges with arbitrary angle. We used three coordinate systems #0, #1, and #2 and considered coordinate transformation. Next, we explained the method to find the diffraction points on two edges. We analyzed the diffracted fields by two edges using the GTD. The numerical

FIGURE 6: Fields diffracted by two wedges for vertical polarized incidence.

calculations were carried out for two wedges of perfect conductor for horizontal and vertical polarized incidence.

From the numerical results, we conclude as follows.

- (i) The diffraction points on two edges with arbitrary angle in horizontal and vertical planes can be confirmed by few repetitions of our method.
- (ii) The number of repetitions is increased when the angles and/or distance to the observation point are increased.
- (iii) When the frequency is doubled, outside the transition region, the single-, double-, and slope-diffracted fields are decreased 3 dB, 6 dB, and 12 dB, respectively.

- (iv) When the wave is incident perpendicularly to parallel edges, the diffracted fields have the same component as incident polarization, but the orthogonal component wave to incident wave is generated by edges with arbitrary angle.

- (v) When the angle between two edges increases horizontally and/or vertically, relatively strong orthogonal polarized wave components appear, but the principal components are the same as the incident wave.

In the future work, we would like to confirm numerical results by experiments.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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