Study of Propagation Characteristic Analysis of a Microstrip Line Placed on Ground Slot Asymmetrically

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Abstract—Recently, printed circuit boards with multi-layer are increasing since advanced technology makes electronic circuits high-density. Then, a number of vias to connect each layer are used and slots are put on a ground. The existence of slots is issue for circuit designs in future. There is the Transmission Line (TL) method which can calculate with short time as an analysis method of transmission line. It is important to consider the effects of slots in by the TL method. In this paper, when the ground slot exists asymmetrically underneath a microstrip line , we analyzed the propagation characteristic and characteristic impedance of a microstrip line with the ground slot in PCB using TL method. In addition, we show the validity of the TL method by using the FDTD method and measurement.

Keywords— *microstrip line,ground slot, transmission line method*

I. INTRODUCTION

Recently, electric circuits become small and high-density electrical technologies have advanced. In order to connect many elements on a small PCB, a high-density multi-layered PCB may be used. And also a number of vias are used in multi-layered printed circuit boards to connect trace on each layer. Then, it is difficult to place sufficiently large ground in the PCB. And also many clearance holes which are used to avoid contact with ground are formed around of the vias. Consequently, ground slots maybe formed if many clearance holes are placed closely on the ground plane. The transfer characteristic changes at the point and the reflection of the signal maybe occurred if such ground slot exists near a transmission line. Thus, the existence of slots may cause significant issues for high-speed PCB designs. There is the Finite-difference time-domain (FDTD) method which calculates electromagnetic fields numerically to analyze easily complex structures such as a PCB with ground slots [1]–[8].

But it is difficult to use the FDTD method for circuit designs because calculation times of the FDTD method are too large to design for practical using. Thus, the analysis method which can design to such a PCB in short time is needed. So, Takamatsu et al suggested analysis method of a microstrip line placed on ground slot symmetrically by the transmission-line (TL) method which can be calculated quickly [9]. However, it is necessary to consider the case of a microstrip line which is placed on a ground slot asymmetrically. In this paper, we analyze the transmission characteristic of a microstrip line asymmetrically above a ground slot in a PCB using TL method. Also, we validate the analysis method with measurement and FDTD result.

II. ANALYSIS USING TRANSMISSION LINE METHOD

When microstrip line is placed above the ground slot, the characteristic impedance of the line changes greatly. The TL model of the microstrip line above the ground slot is shown in Fig. 1. The ground slot with width W_s and length l is placed at center of the PCB. We defined that the left edge of the slot is on $x = 0$, and the right edge of the slot is on $x = l$. In this model, the characteristic impedance of the microstrip line without the slot is Z_0 and that of the microstrip line above the ground slot ($0 \leq x \leq l$) is Z_s. And also the propagation constant of the microstrip line above the slot is $\gamma_s = \alpha_s + j\beta_s$, where α_s is the attenuation constant and β_s is the phase constant. We will calculate the incident and reflect voltages at $x = 0$ and $x = l$. In this paper, the conducting loss is ignored since the influence is too small for the propagation characteristics. The voltages $V(x)$ and the currents $I(x)$ on the transmission line are shown as

$$V(x) = Ae^{-\gamma_s x} + Be^{\gamma_s x} \qquad (1)$$

$$I(x) = \frac{A}{Z_s}e^{-\gamma_s x} - \frac{B}{Z_s}e^{\gamma_s x} \qquad (2)$$

where A means the magnitude of incident voltage and B means the magnitude of reflection voltage, respectively. The voltage V_0 and the currents at $x = 0$ are $V(0) = V_0 - Z_0 I_0$, $I(0) = I_0$ respectively. And at $x = l$, $V(l)$ and $I(l)$ are shown as

$$V(l) = Ae^{-\gamma_s l} + Be^{\gamma_s l} \qquad (3)$$

$$I(l) = \frac{A}{Z_s}e^{-\gamma_s l} - \frac{B}{Z_s}e^{\gamma_s l}. \qquad (4)$$

Also, using $V(l) = Z_0 I(l)$ and the equation (3) and (4), A and B are shown as

$$A = \frac{(Z_0 + Z_s)e^{\gamma_s l}}{(Z_0 - Z_s)e^{-\gamma_s l}} B. \qquad (5)$$

S_{11} obtained by equation (5) is defined as

$$S_{11} = \frac{B}{A} = \frac{(Z_s^2 - Z_0^2)e^{\gamma_s l} - (Z_s^2 - Z_0^2)e^{-\gamma_s l}}{(Z_s + Z_0)^2 e^{\gamma_s l} - (Z_s - Z_0)^2 e^{-\gamma_s l}}. \qquad (6)$$

The propagation coefficient S_{21} is defined as

$$S_{21} = \frac{V(l)}{A} = \frac{4 Z_s Z_0}{(Z_s + Z_0)^2 e^{\gamma_s l} - (Z_s - Z_0)^2 e^{-\gamma_s l}}. \qquad (7)$$

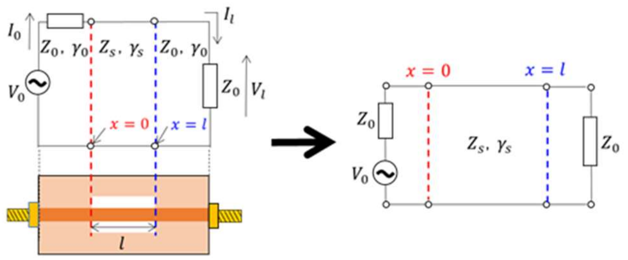


Fig. 1. Transmission line model of TL

III. DERIVATION OF CHARACTERISTIC IMPEDANCE AND PHASE CONSTANT OF A MICROSTRIP LINE ABOVE A GROUND SLOT

The characteristic impedance Z_s and the phase constant β_s of the microstrip line above the ground slot are derived by the finite element method (FEM) [10].

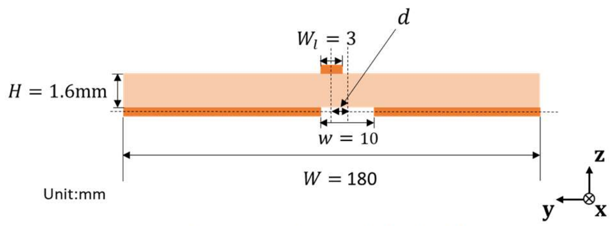


Fig. 2. Analysis model of FEM

We show analysis model of FEM as Fig.2. The distance from center of the trace to center of ground slot is defined d. we calculate C_0 and C_s per unit length capacitance. we analyze with varying $d = 0\sim6$ mm. The PCB consists of FR4. Slot width W_s is 10mm. Then, we substitute into the following equation and derive Z_s and β_s. Also v is the light speed.

$$L = \frac{1}{v^2 C_0} \qquad (8)$$

$$Z_s = \sqrt{L C_s} \qquad (9)$$

$$\beta_s = 2\pi f \sqrt{L C_s} \qquad (10)$$

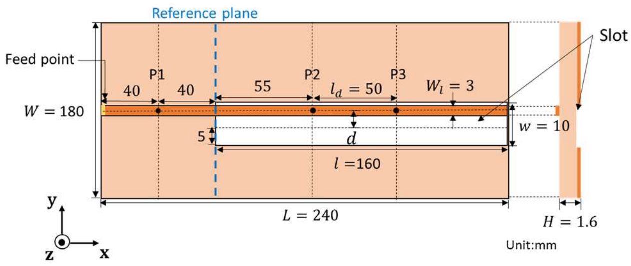


Fig. 3. Analysis model of FDTD method

We show analysis model of the FDTD method as Fig.3. We defined that the incident voltage V_i and the reflected voltage V_r at the observation point P1, and the currents I_{t2} and I_{t3} at the observation point P2 and observation point P3, respectively. We analyze them with varying $d = 0\sim6$ mm. Then, we obtain the reflection coefficient S_{11} from V_i and V_r. In order to obtain S_{11}, we compensate of electrical rength. And we obtain the phases θ_{t2} and θ_{t3} from I_{t2} and I_{t3} respectively. Derivation of Z_s and β_s is used the following equation (11). Z_0 is the characteristic impedance of the line when there is without slot, and l_d is the distance between observation point 2 and observation point 3.

$$Z_s = \left| Z_0 \frac{1 + S_{11}}{1 - S_{11}} \right| \qquad (11)$$

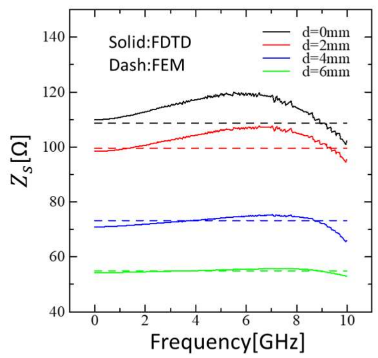


Fig.4. Absolute value of characteristic impedance Z_s

We show the result that the absolute value of the characteristic impedance and the result of the phase constant β_s obtained by the FEM and the FDTD method in Fig.4 and Fig.5 respectively. In Fig.4, there is no frequency dependency and it has a constant value in the FEM. In the FDTD method, we could get the characteristic impedance corresponding to the frequency. When d is small, the difference between value of the FEM and the value of the FDTD method becomes larger as the frequency becomes larger. The reason is that the effect of the slot can't be properly considered in the finite element method. However, when d is large and the influence of the slot is small, the characteristic impedance of the line approaches 50Ω, and the graphs of the FEM and the FDTD method almost agree.

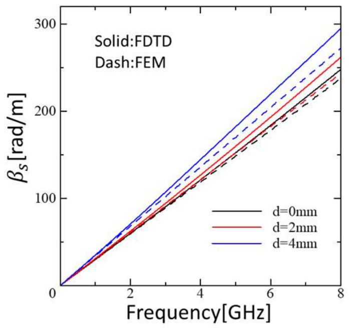


Fig.5. the phase constant β_s on the ground slot

Next, looking at the results of the phase constants in Fig.5.The overall tendency is slightly lower than the FDTD method, in which the calculated value of the finite element method is slightly lower. When d is small, that is, when it is directly under the microstrip line, the phase constant becomes small because the capacitance between the line and the ground is the minimum. However when the center distance d is large, since the capacitance increases, and the phase constant becomes big.

IV. MEASUREMENT AND ANALYSIS OF PROPAGATION CHARACTERISTIC

A) *Stracture of measurement substrate*

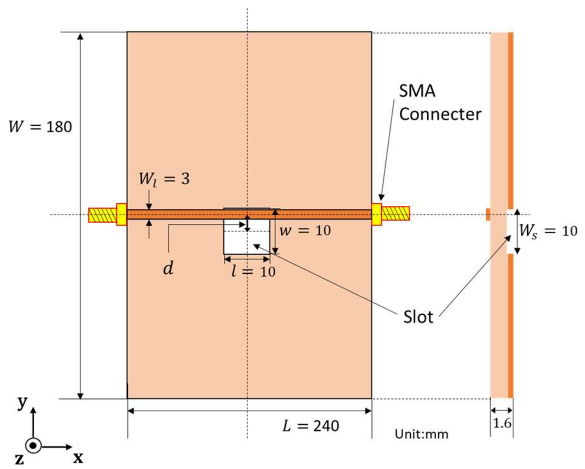


Fig.6. Structure of PCB used for measurrement

In order to investigate the validity of the proposed method, we measure and analyze the FDTD method. The substrate is made of FR4 with relative dielectric constant $\varepsilon_r = 4.4$. The microstrip line is placed at the center on the substrate. At this time, the width of the microstrip line is 3mm and the characteristic impedance is about 50Ω. Then, the slot that the slot length l is 10mm and the slot width w is 10mm is placed underneath the line. And, d is 2mm.

B) *Stracture of analysis substrate*

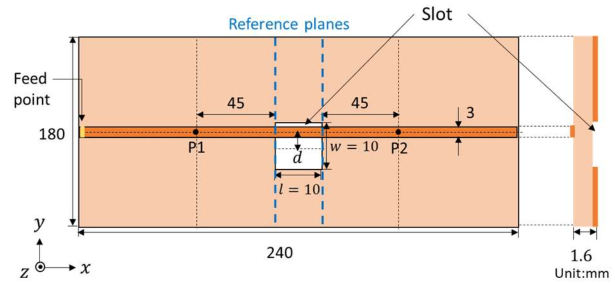
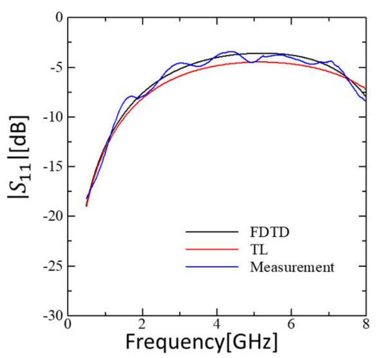


Fig.7. Structure of PCB used for FDTD metod

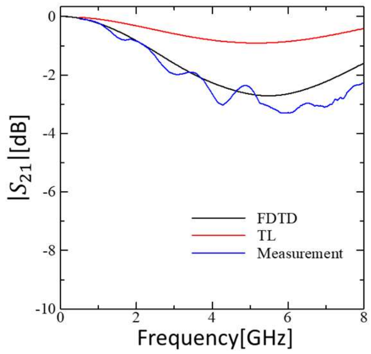
The stracture of the sbstrate used for FDTD method is shown as Fig.7. One surface of the substrate is used as a condoctor ground and microstrip line with a width $W_l = 3$mm is placed on the other surface. Also, the distance between the center of the line and the slot is d(mm). In the analysis, in order to eliminate the influence of reflection occurring at the end of the line and terminate matching, the number of time steps was appropriately determined. In addition , as shown in Fig.7, we analyze the voltage at the observation points 1 and 2. Also we converted it into the result on the reference plane by conpensation electical rength.

C) *Comparison of measurement results and analysis results*

The slot length L_s is 10 mm and the slot width W_s is 10 mm, and reflection and transfer characteristics are analyzed by TL method and FDTD method. Further, we made a substrate about the model of Fig.6 and measured. On the measuring board, SMA connectors were connected to both ends of the line. S_{11} and S_{21} were measured using the VNA(KEYSIGHT E5071C), and calibration was carried out using TRL calibration kit.

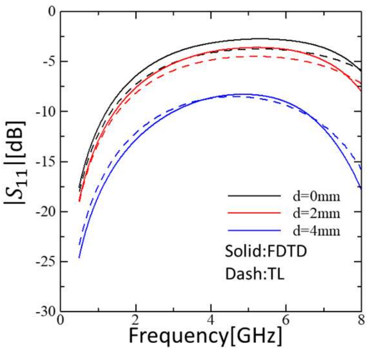


(a) Amplitude S_{11}

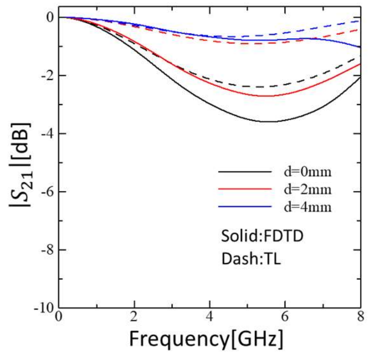


(b) Amplitude S_{21}

Fig.8. Transmission characteristics (d = 2mm)



(a) Amplitude S_{11}



(b) Amplitude S_{21}

Fig.9. Transmission characteristics about measurement and analysis

We show refrection characteristic S_{11} and transfer characteristic S_{21} at $d = 2$mm in Fig.8 (a) and (b), respectively. From results in Fig.8, the validity of the analysis method was shown. Because, analysis results of FDTD method and TL method almost agree with each other. However , there is a tendency for slight differences and waveforms to rise and fall when compered with measurements. For these reasons, it can be considered that cann't be ignored and commmon mode currents and losses due to the length of the substrate. Next, the result of the propagation characteristics when the center distance d is changed to 0∼4 mm are shown in Figs.9 (a) and (b), respectively. From the results shown in Fig.9 (a), the reflection characteristic S_{11} becomes the maximum when the slot is arranged right underneath the line. As the center distance d increases, the influence on reflection decreases. At high frequency, there is the difference between the FDTD mothod and measurement. Because the dielectric loss and the conducting loss are not considered. We will consider them in the future task to improve accuracy. Futher, from Fig.9(b), as the center distance d increases, matching of the characteristic impedance becomes favorable, and it is understood that the transfer characteristic S_{21} tends to improve as opposed to the reflection characteristic S_{11}.

V. CONCLUSION

In this paper, we aimed to analyze the propagation characteristics of a microstrip line asymmetrically placed on ground slot by TL method. Futhermore, in order to immprove the accuracy of the TL method, the characteristic impedance and the phase constant of the line on the slot were considered. For comparion, analysis and measurement by the FDTD method were carried out. In this way, it was possible to confirm the influence of the propagation characteristic of the line to the center distance d and the ground slot. In the future, in order to further improve the analysis accuracy of the TL method, it is necessary to consider unnecessary electromagnetic radiation.

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