Full Wave Analysis of Propagation Characteristics of a Through Hole using the Finite-Difference Time-Domain Method

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ABSTRACT

A full wave analysis of the propagation characteristics of a through hole was carried out using the finite-difference time-domain (FD-TD) method. The results were compared with measured values. Agreement between computed results and measured ones was excellent from DC to high frequencies. As a result, it is shown that at high frequencies, radiation is at a significant level. The frequency characteristics of radiation depend on the structure of the through hole, especially its rod diameter and microstrip connecting angle.

INTRODUCTION

In line with the trend toward miniaturization of electrical devices and high density packing, multilayered electronic circuits are in increasing use. Thus, it is essential to analyze the propagation characteristics of a through hole for designing multilayers, in which through holes exert a strong influence on circuit performance. The through hole has a complex three dimensional structure consisting of microstrips, a rod, lands and a clearance hole. This complex structure makes it very difficult to analyze the propagation characteristics quantitatively. The traditional numerical approaches [1-2] have lacked versatility and strictness. Consequently, rigorous analysis of a through hole has not been carried out. There are, in fact, losses at points where signals are shunted through through holes. Furthermore, investigations have not yet reported on dependence of losses upon the angle at which the microstrips on either side of the through hole meet (hereafter referred to as the 'microstrip connecting angle'). The FD-TD method is considered effective and suitable for this analysis because of its versatility and its full wave analysis. Moreover, it is necessary to predict the broad band characteristics to estimate the performance of a through hole. A time domain analysis such as FD-TD [3-5] has the advantage that the broad band characteristics can be obtained in a single computer run using Fourier transform. This correspondence investigates the propagation characteristics of a through hole using the FD-TD method. Good agreement between computed results and experimental ones is confirmed. It is shown that radiation is a significant factor at high frequencies. The frequency characteristics of radiation depend on the structure of a through hole, especially its rod diameter and microstrip connecting angle.

NUMERICAL APPROACH

The FD-TD method has been used in many kinds of electromagnetic problems [3-6]. In this method, the two Maxwell's curl equations are discretized both in time and space, and the field values on the nodal points of the lattice are calculated in a leap-frog algorithm.

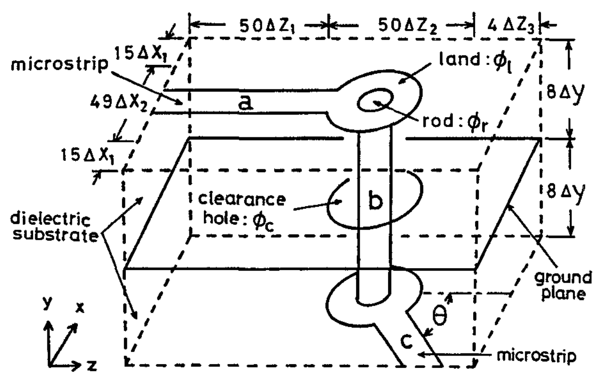

Fig.1. Through hole in three multilayers.
(ε_r=3.4, Δx_1=0.3mm, Δx_2=0.1mm, Δy=0.2mm, Δz_1=0.3mm, Δz_2=0.1mm, Δz_3=0.3mm).

Fig.1 shows a diagram of the through hole model used in this analysis. It has three conductor layers. Microstrip **a** meets microstrip **c** at the angle θ. There are assumed to be air regions over microstrip **a** and under microstrip **c**, but they are not shown in Fig.1 for simplicity. The staircasing approximation is used for modeling of the lands, clearance hole and rod conductor. The diameter of the lands ϕ_l is 3.9mm, the diameter of the clearance hole ϕ_c is 3.9mm, and the diameter of the rods are ϕ_{r1} =0.7mm and ϕ_{r2} =1.5mm. In this model, a variable size mesh is used to reduce demands on memory. The spatial increments are Δx_1=0.3mm, Δx_2=0.1mm, Δy=0.2mm, Δz_1=0.3mm, Δz_2=0.1mm, and Δz_3=0.3mm, and the time increment is Δt=0.222ps. The substrate, both for calculation and for the physical model, mainly consisted of polyphenylene oxide (PPO) resin, which we have developed for microwave printed circuit boards. The permittivity of the substrate is assumed to be ε_r=3.4 at all frequencies. In this analysis, dielectric loss and conductor loss are neglected, and the thickness of the conductor is considered zero for simplicity. On the xy-plane at $z=4\Delta z_1$, a raised cosine pulse is applied under microstrip **a** in Fig.1. The calculated electric field component (E_y) follows this form (1).

$$E_y = 1-\cos(2\pi f_{band} t) \quad : \quad 0 \le t < 1/f_{band}$$

$$E_y = 0 \quad : \quad 1/f_{band} \le t$$

$$f_{band} = 12.0 \text{ (GHz)}. \tag{1}$$

The time history of the reflected wave at the point (x_{ar}, z_{ar}) where $x_{ar}=15\Delta x_1+25\Delta x_2$ and $z_{ar}=2\Delta z_1$ were calculated. The time history of the original incident wave was calculated for the point $x_{ai}=15\Delta x_1+25\Delta x_2$ and $z_{ai}=21\Delta z_1$. The time history of transmitted waves were calculated at different locations, depending on the microstrip connecting angle θ. When $\theta=0°$, the observation point corresponded to $x_{c1}=15\Delta x_1+25\Delta x_2$, $z_{c1}=50\Delta z_1+50\Delta z_2+2\Delta z_3$. For $\theta=90°$, the observation point corresponded to $x_{c2}=13\Delta x_1$, $z_{c2}=50\Delta z_1+25\Delta z_2$. The obtained data were fast Fourier transformed and normalized in terms of the incident wave spectrum to obtain scattering parameters S_{11} and S_{21}. Those were defined as

$$S_{11}(\omega) = V_{ref}(\omega)/V_{inc}(\omega)$$

$$S_{21}(\omega) = V_{out}(\omega)/V_{inc}(\omega) \tag{2}$$

where $V_{ref}(\omega)$ is the reflection voltage, $V_{inc}(\omega)$ is the incident voltage, and $V_{out}(\omega)$ is the transmission voltage. The absorbing boundary condition [7] is adopted on the surfaces of the analyzed region. The authors have confirmed that reflections from absorbing boundaries may be neglected.

RESULTS AND DISCUSSION

The authors first calculated the scattering parameters $|S_{11}|$ and $|S_{21}|$ of a through hole using the FD-TD method.

Fig.2 shows the magnitude of the reflection coefficient $|S_{11}|$. Fig.3 shows the magnitude of transmission coefficient $|S_{21}|$. In order to verify the computed results, we measured the scattering parameters using a network analyzer. The rod diameter of the through hole in the experiment was ϕ_{r1}=0.74mm and ϕ_{r2}=1.58mm. The diameter of the land and clearance hole was about 3.9mm. The computed results show excellent agreement with the measured ones from DC to high frequencies. In this analysis, $|S_{21}|$ generally drops with increase in frequency. Low frequency waves appear to propagate well, but high frequency waves do not.

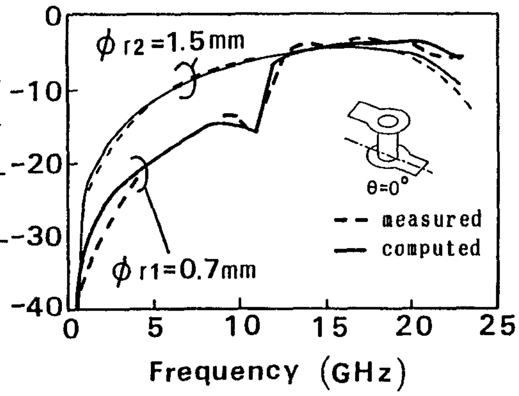

Fig.2. Frequency characteristics of $|S_{11}|$. (microstrip connecting angle θ =0°, the diameter of the lands ϕ_l=3.9mm).

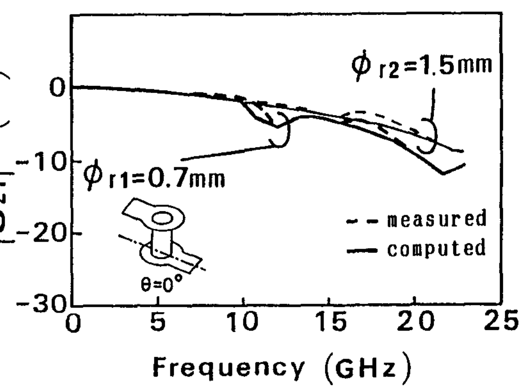

Fig.3. Frequency characteristics of $|S_{21}|$. (microstrip connecting angle θ =0°, the diameter of the lands ϕ_l=3.9mm).

Fig.4 and Fig.5 show the computed radiation power P_c in the simulation, and the measured value $P_m=1-|S_{11}|^2-|S_{21}|^2$ from the experimental data $|S_{11}|$ and $|S_{21}|$ for different through hole structures. In this simulation, we confirmed that the energy conservation law is satisfied in terms of $|S_{11}|, |S_{21}|$ and radiation power. Agreements in Fig.4 and Fig.5 indicate that lost energy P_m in the experiment corresponds to the radiation power. In Fig.4, the rod diameter is ϕ_{r1}=0.7mm. The radiation frequency shows two peaks corresponding to the rod diameters. When the land diameter was 3.9mm, a radiation peak appeared at about 12.2GHz (the solid line in the figure). When the diameter of the land was 3.3mm, the peak appeared at about 14.0GHz (the dotted line in the figure). The ratio of peak frequencies is almost equal to the inverse ratio of the land diameters. This implies that the radiation is mainly caused by resonance of the lands. This phenomenon corresponds to the dip at the same frequencies in Fig.2 and Fig.3.

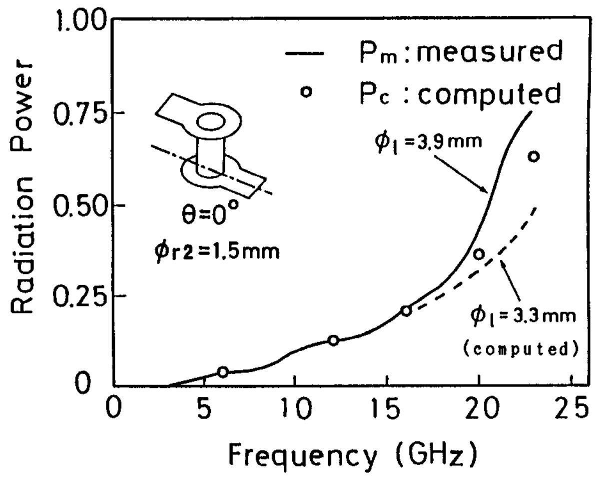

Fig.5. Radiation power as it varies with frequency. (microstrip connecting angle $\theta=0°$, ϕ_{r2}=1.5mm).

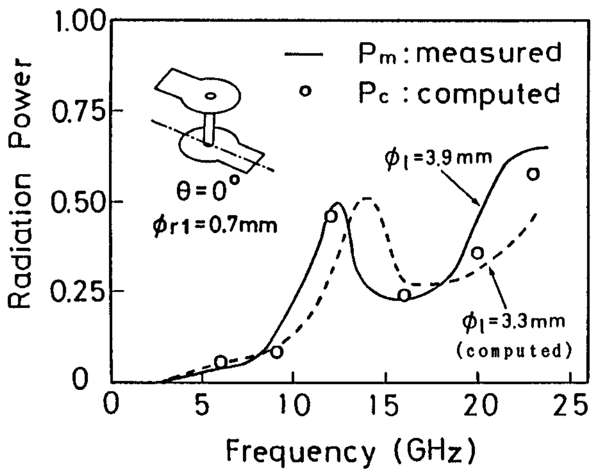

Fig.4. Radiation power as it varies with frequency. (microstrip connecting angle $\theta=0°$, ϕ_{r1}=0.7mm).

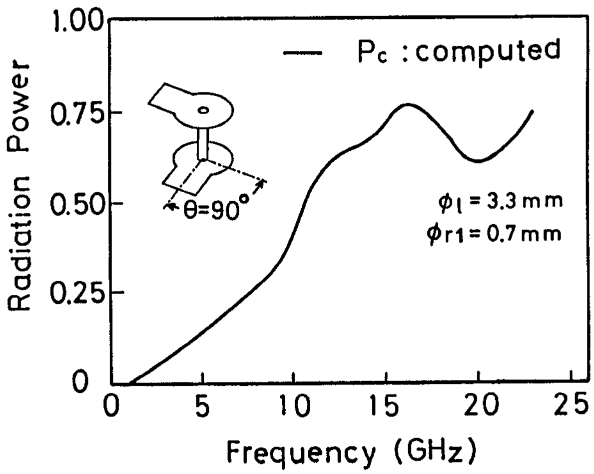

Fig.6. Radiation power as it varies with frequency. (microstrip connecting angle $\theta=90°$, ϕ_{r1}=0.7mm).

In Fig.5, the rod diameter is ϕ_{r2}=1.5mm. No radiation peak appears for different diameters of lands with this larger rod.

In Fig.6, the rod diameter is ϕ_{r1}=0.7mm, and the microstrip line angle is $\theta=90°$. Fig.6 shows only the computed results of radiation power. The through hole with a $\theta=90°$ microstrip connecting angle radiates more strongly than the hole with a $\theta=0°$ angle. It appears that radiation strongly depends on the structure of the connecting angle at the through hole.

Finally, we computed the time response. Fig.7 and Fig.8 show the impulse time response of reflection waves in the through hole with a $\theta=0°$ microstrip connecting angle. In Fig.7, the rod diameter is ϕ_{r1}=0.7mm. In Fig.8, the rod diameter is ϕ_{r2}=1.5mm. The computed results showed good agreement with the measured ones for the phase. There was a small difference in magnitude between the measured and computed values; the reason for this was the attenuation at the connections from the coaxial lines to the microstrips at each end of the DUT (device under test). This wave form shows that this through hole structure has the characteristics of the shunt C type.

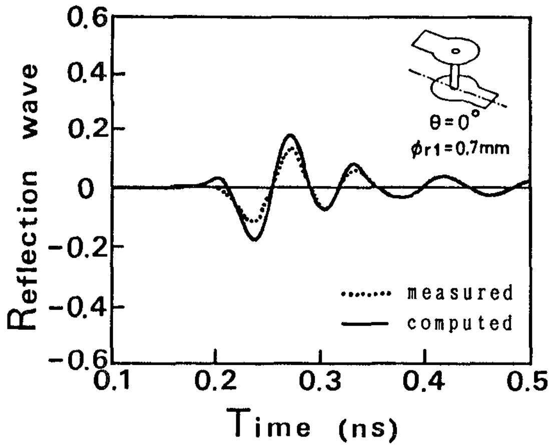

Fig.7. Time response of reflected wave.
(microstrip connecting angle $\theta=0°$, $\phi_{r1}=0.7\text{mm}$).

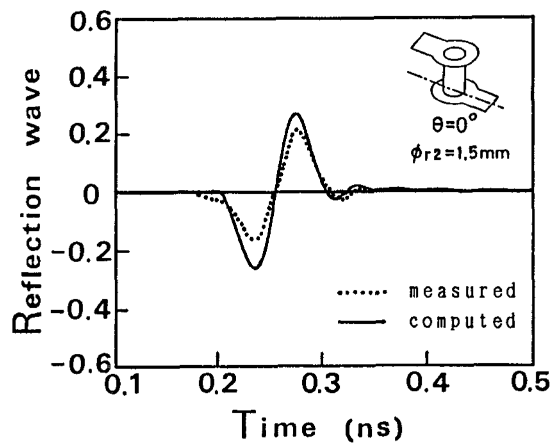

Fig.8. Time response of reflected wave.
(microstrip connecting angle $\theta=0°$, $\phi_{r2}=1.5\text{mm}$).

The permittivity of PPO substrate changes about 6 % between the low and high frequency regions. An investigation which takes the dispersive characteristics of the substrate in the time domain into account is in progress [8]. The computations were executed on a Hitachi S820/80 supercomputer. The CPU time for simulation was about 140 seconds.

CONCLUSION

A full wave analysis of the propagation characteristics of a through hole of a complex three dimensional structure was carried out using the FD-TD method. The computed results showed excellent agreement with the measured results from DC to the high frequency region for the case where the microstrips meet at an angle of $\theta=0°$ at the through hole (the 'microstrip connecting angle'). Radiation at a through hole is clearly not a negligible factor for high frequencies. Radiation effect strongly depends upon the microstrip connecting angle. The results obtained in this correspondence show the validity and effectiveness of the FD-TD method for analyzing the through hole. The method can provide quantitative and accurate physical values which are difficult to measure directly, such as radiation phenomena.

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