JOURNAL OF THE KOREAN INSTITUTE OF ELECTROMAGNETIC ENGINEERING AND SCIENCE, VOL. 9, NO. 2, JUN. 2009 JKIEES 2009-9-2-08

A Study on the Coupling of a Flanged Parallel-Plate Waveguide to a Slit in a Nearby Conducting Screen for Near-Field Scanning Microscopy

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Abstract

The problem of electromagnetic coupling between a slit fed by a flanged parallel-plate waveguide(PPW) and a slit in an infinite nearby conducting screen parallel to the flanged ground conductor is studied as a simplified problem for a near-field scanning microscopy(NSM). The method of moments isused to solve the coupled integral equations for the electric field distributions over the slits. The performance of the proposed apparatus as an NSM is tested by examining the effects of some geometrical parameters on the equivalent slit admittance and coupled powers through the slits.

Key words : Coupling; Slit, Near-Field Scanning Microscopy(NSM), Parallel-Plate Waveguide(PPW).

Ⅰ. Introduction

The millimeter wave scanning microscope is a useful device for the imaging of complex microwave integrated circuits(MICs)[1]. The near-field scanning microscopy (NSM) with high resolving power employs a probe of sub-wavelength size and a small object located in a near-field region. Since the resolution of a near-field scanning microscope depends on the probe-to-object distance as well as the probe size, the probe cannot be separated from the object[2]. Studies on several types of microwave near-field probes such as circular aperture[3], coaxial probe[4], small loop[5], and flanged parallel-plate waveguide[6] have been reported.

This study considers simplified near-field scanning microscope geometry(see Fig. 1) constituted by a flanged parallel-plate waveguide(PPW) as a probe and a slit in a nearby conducting screen that is parallel to the flanged ground conductor as an object. The problem of electromagnetic coupling between the PPW and the outside region through the slits is studied when the TEM mode wave in the PPW is incident on the slit. By enforcing the continuity of tangential electromagnetic fields across the slits, a set of coupled integral equations for the electric field distributions over the slits is obtained and solved by using the method of moments. The effects of the geometrical parameters of the structuresuch as slit widths, slit-to-slit distance, and waveguide height on the performance of the proposed geometry as an NSM have been investigated here. The results demonstrate that high resolution with this structure is feasible.

Ⅱ. Theory

Fig. 1 shows a cross-sectional view of a flanged parallel-plate waveguide(PPW)(region 1, $z \leq 0$) and a slit-perforated conducting screen($z=d$) parallel to the ground plane($z=0$). In Fig. 1, h is the guideheight, w_0 is the width of slit S_0, X_1 is the lateral offset of slit S_1 from the origin, w_1 is the width of slit S_1, and d is slit-to-slit distance. The y-component of the TEM magnetic field incident on the slit region($z=0$) can be given by

$$H_y^i = \frac{V_0}{\eta_1 h} \exp(-jk_1 z) \tag{1}$$

where V_0 is the potential difference between two plates, $k_1 (= k_0 \sqrt{\varepsilon_{r1}}$, $k_0 = \omega \sqrt{\mu_0 \varepsilon_0} = 2\pi / \lambda_0)$ is the wave number, and $\eta_1 (= \eta_0 / \sqrt{\varepsilon_{r1}}$, $\eta_0 = \sqrt{\mu_0 / \varepsilon_0}$) is the intrinsic impedance of the dielectric inside the PPW.

The equivalence principle is employed to divide the original problem into three equivalent situations, as shown in Fig. 2. The slits S_0 and S_1 are closed with a perfect conductor and the electric fields originally present in the slits are supplied by attaching the equivalent magnetic current sheets $\pm \underline{M}_0 (= \pm \hat{y} E_x^{S_0} = \pm \hat{y} E_x$ over $S_0)$ and $\pm \underline{M}_1 (= \pm \hat{y} E_x^{S_1} = \pm \hat{y} E_x$ over $S_1)$ on both sides of the closed slits, respectively.

By expressing the electromagnetic fields in the regions in terms of the fields due to the incident TEM wave and the magnetic current sheets over S_0 and S_1, we find that the expressions for the y-component mag-

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Manuscript received April 24, 2009 ; revised June 5, 2009. (ID No. 20090424-020J)

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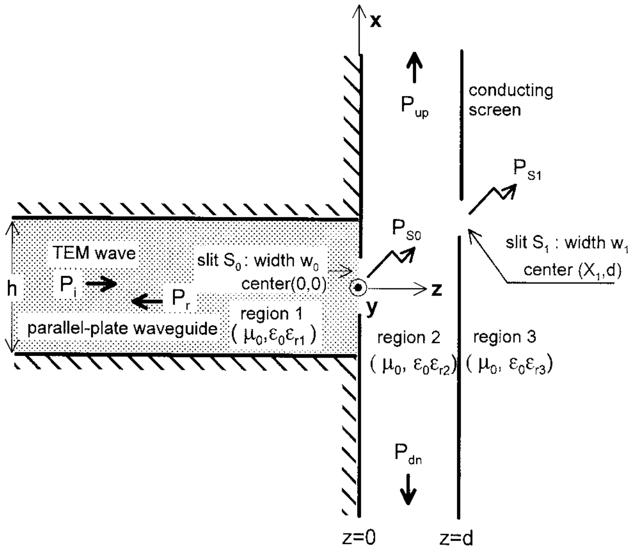

Fig. 1. Geometry under consideration.

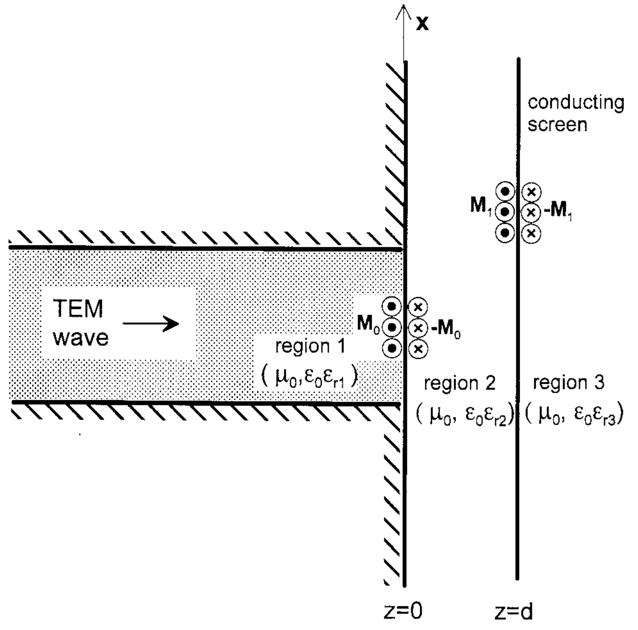

Fig. 2. Equivalence for the three regions.

netic field in each region are

$$H_{y1} = H_{y1}^{sc} + H_{y1}^{M_0} \tag{2a}$$

$$H_{y2} = -H_{y2}^{M_0} + H_{y2}^{M_1} \tag{2b}$$

$$H_{y3} = -H_{y3}^{M_1} \tag{2c}$$

where the subscripts denote the y-component and the region. The superscripts represent the sources of the fields. $H_y^{sc}\,[= 2V_0\cos(k_1 z)/(\eta_1 h)]$ is the so-called short circuit magnetic field[7]. The detailed expressions for each term in (2a)~(2c) are available from the earlier works[7],[8]. The continuity of tangential fields across the slits S_0 and S_1 leads to the coupled integral equations for the magnetic current distributions, which are equal to the tangential electric field distributions $E_x^{S_0}$ and $E_x^{S_1}$ over the slits. By employing the pulse(piecewise constant) basis function and thepoint matching method, the equations are solved numerically using the method of moments.

From the knowledge of the electric distributions $E_x^{S_0}$ and $E_x^{S_1}$, one can obtain all the field components in each region. The quantities of interests can then be computed. These are the voltage reflection coefficient Γ_v at S_0(i.e., at z=0$_-$), the normalized equivalent admittance $y_s\,[= Y_s/Y_c = g_s + jb_s = (1-\Gamma_v)/(1+\Gamma_v),\ Y_c = 1/(\eta_1 h)]$ of S_0[8], the reflected power P_r from S_0, the coupled power P_{S0} through S_0, the guided powers P_{up} and P_{dn} along the guiding structure(formed between the flanged ground conductor at z=0 and the infinite conducting screen at z=d), and the coupled power P_{S1} through S_1 into region 3.

Ⅲ. Results and Discussions

In this section, the effects of some geometrical parameters such as guideheight h, slit widths w_0 and w_1, and distance d between the flanged PPW(z=0) and slit-perforated conducting screen(z=d) on the quantities of interests, such as the coupled powers P_{S0} and P_{S1} through the slits S_0 and S_1, and the equivalent slit admittance y_s=g_s+jb_s are examined. Here, all the power quantities(P_{S0}, P_{S1}, P_{up}, and P_{dn}) are normalized with respect to the incident TEM mode power P_i, for convenience, by setting P_i=1.

Fig. 3 shows the plot of the coupled power P_{S1} through the slit S_1 into region 3 for d/λ_0=0.02=0.02 and

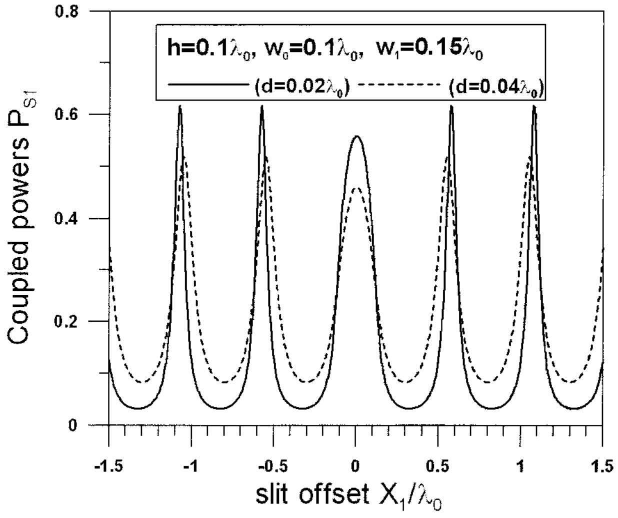

Fig. 3. Coupled power P_{S1} against the slit offset X_1.

0.04 against lateral displacement X_1 of the slit S_1 from the origin. Here, the guideheight $h/\lambda_0=0.1$, the slit width $w_0/\lambda_0=0.1$(i.e., $w_0=h$), and the dielectric constants of all the materials are assumed to be the same as that of the free space(i.e., $\varepsilon_{r1}=\varepsilon_{r2}=\varepsilon_{r3}=1$). In Fig. 3, it is seen that P_{S1} attains maxima at offsets that approach multiples of a half wavelength($|X_1|\approx n\lambda_0/2$, $n=1,2,3,\cdots$), in addition to its maximum at zero offset($X_1=0$). This feature of multiple maxima would seem unfavorable to microscopy applications but, as pointed out in [9], it can be overcome by utilizing a multiple-frequency source, thereby significantly enhancing the desired maximum at zero offset while retaining virtually the same remaining maxima. It is also observed that the peak becomes broader and its magnitude decreases as the distance d gets larger. This implies that the nearer the screen with the slit S_1(as an object) is to the flanged PPW(as a probe tip), the higher the resolution of its image is.

The reason for the occurrence of periodic peaks at $|X_1|\approx n(\lambda_0/2)$(n=1,2,3,···) can be explained here. As mentioned already, a PPW structure is formed between the infinite flange of the flanged PPW($z=0$) and the infinite conducting plane($z=d$). This PPW structure can be thought of as being perturbed by two slits, i.e., by one slit S_1 in one plane($z=d$) and the other slit S_0 in the other plane($z=0$). When the guideheight is much smaller than the wavelength, as in the present case(i.e., $d\ll\lambda_0$), even a very narrow transverse slit behaves almost like an open circuit, as discussed in [10]. For this reason, the PPW region that is roughly between the two slit centers($0<x<0.5\lambda_0$) can be viewed as a half-wavelength transmission line resonator, whose ends are terminated by very small admittances of the slits S_0 and S_1. Because of this, a strong mode field is excited inside the resonator by a feeding PPW($z<0$). This results in a maximum coupling P_{S1} through the slit S_1 at $X_1\approx\lambda_0/2$ and, as such, the occurrence of maxima of P_{S1} at $|X_1|\approx n(\lambda_0/2)$ might be explained.

Next, we investigate the effect of w_0/h on the coupled power P_{S1}. Fig. 4 shows the variation of P_{S1} against the offset X_1 for different slit widths and guide heights($h/\lambda_0=0.02$ and 0.2). In Fig. 4, it is observed that in the case of $h=0.2\lambda_0$, as w_0/h is decreased(due to the decrease in w_0), P_{S1} at $X_1=0$(non offset case) is also decreased. However, when the guideheight h is decreased to a much smaller value than the wavelength(i.e., $h=0.02\lambda_0$), the coupled power P_{S1} is only marginally affected by the slit width w_0, as shown in Fig. 4.

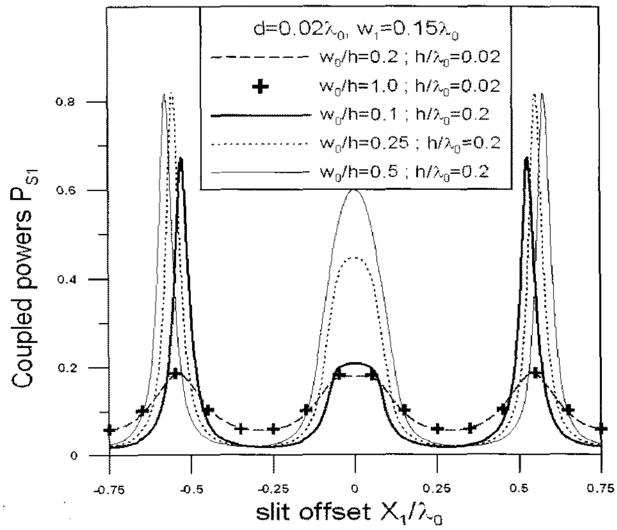

Fig. 4. Coupled power P_{S1} for various values of w_0/h.

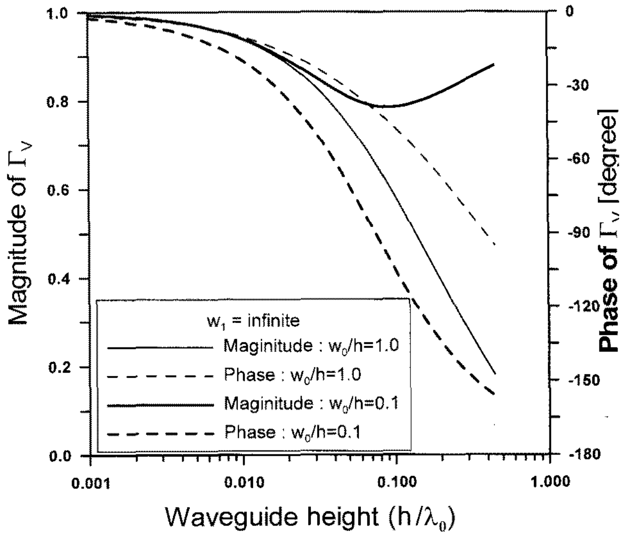

Fig. 5. Characteristics of flanged PPW without slitted conducting screen.

The characteristics of the flanged PPW without the slitted conducting screen at $z=d$ can explain the reason for the small variation of the coupled power P_{S1} against the slit width w_0 for the case of $h=0.02\lambda_0$ in Fig. 4. In Fig. 5, the voltage reflection coefficient $\Gamma_v[=-(y_s-1)/(y_s+1)]$ for $w_0/h=1$ and $w_0/h=0.1$ is plotted. As shown in Fig. 5, when the guideheight h is much smaller than the wavelength λ_0, the slit S_0 in the flanged ground plane behaves as an open circuit(i.e., $\Gamma_v\approx 1\angle 0°$), irrespective of the ratio w_0/h. Hence the characteristics of the flanged PPW are not significantly affected by the slit width w_0, even if it is small.

In Fig. 6, the equivalent slit admittance $y_s=g_s+jb_s$, seen at $z=0$ looking toward the slit S_0, is plotted along with the coupled power P_{S0} through the slit S_0. When $w_1=\infty$, the admittance has small conductance g_s and relatively large susceptance b_s for the case of narrow slit

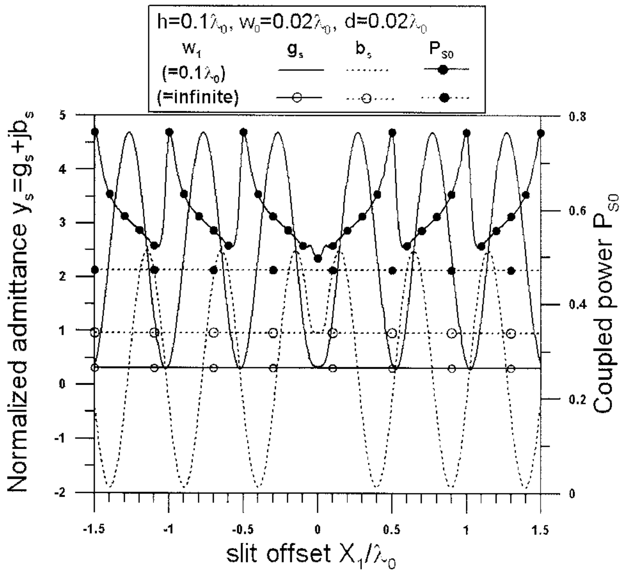

Fig. 6. Equivalent slit admittance $y_s = g_s + jb_s$ of the slit S_0.

S_0. However, when $w_1 = 0.1\ \lambda_0$, for example, and the slit is offset at $|X_1| \approx \lambda_0/2$, the admittance has almost zero susceptance b_s. In contrast, the conductance g_s remains nearly the same as that for the case of $w_1 = \infty$. This cancellation of susceptance is thought to be due to the resonance of the cavity formed along the x-axis between two slits S_0 and S_1. On the other hand, for the case of the peak at zero offset, the conductance is observed to be increased, although the change is small and barely indiscernible, as shown in Fig. 5. In contrast, the susceptance remains almost the same as that for the case of $w_1 = \infty$.

Ⅳ. Conclusions

The problems of electromagnetic coupling through a slit in a flanged PPW, and then into a half-space beyond a slit-perforated conducting screen placed in front of the flanged PPW, have been investigated as a simplified problem for a near-field scanning microscopy(NSM). The problems arising when the TEM wave in the PPW is incident on the slit are solved by usingthe method of moments. The performance of the geometry as an NSM has been tested by examining the variation of the coupled power through the slits beyond the conducting screen against the lateral displacement of the slit from the center of the flanged PPW. In addition to the coupling peak at zero offset, periodic peaks are also observed when the displacement approaches multiples of half wavelengths. The mechanisms of the occurrence of the coupling peaks have been explained qualitatively from the viewpoint of cavity resonance and equivalent admittance.

This work was supported by the 2nd stage of Brain Korea 21(BK21).

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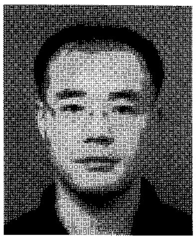

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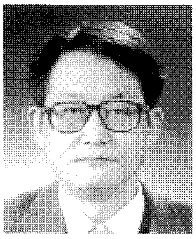

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