근접주사현미경의 관점에서 플랜지된 평행평판 도파관과 근접도체스트립과의 결합에 관한 연구

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A Study on the Coupling of a Flanged Parallel-Plate Waveguide to a Nearby Conducting Strip from the Viewpoint of Near-Field Scanning Microscopy

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요 약

본 논문에서는 플랜지된 평행평판도파관으로 급전된 슬릿과 이에 평행하고 근접하는 도체 스트립과의 전자기적인 결합문제를 단순화된 근접주사현미경의 관점에서 연구하였다. 슬릿의 등가어드미턴스, 슬릿근처 도파관 내부 및 외부의 무효전력, TEM파 전압반사계수의 크기 및 위상 등의 변화결과로부터 플랜지된 평행평판도파관의 특성을 조사하였다. 제안된 구조의 근접주사현미경으로서의 성능을 다양한 구조적인 파라미터들(도파관 높이, 슬릿의 폭, 스트립의 폭, 슬릿과 스트립 간격, 슬릿 폭과 도파관 높이의 비)이 TEM파 전압반사계수의 크기와 위상에 미치는 영향을 관찰하여 점검하였다. 슬릿으로부터 스트립의 변위에 따른 전압반사계수의 변화결과로부터 도파관의 높이가 작을 때 보다 높은 주사해상도를 얻을 수 있음과 반사계수의 크기변화에 비해 위상변화가 훨씬 민감함을 확인하였다.

ABSTRACT

In this paper, the problem of electromagnetic coupling between a slit fed by a flanged parallel-plate waveguide (FPPW) and a nearby conducting strip parallel to the slit is studied as a simplified problem for a near-field scanning microscopy (NSM). The characteristics of the FPPW are investigated from the results for the variations of the equivalent slit admittance, the reactive powers near the slit inside and outside the FPPW, the magnitude and phase of the voltage reflection coefficient of the TEM wave. The performance of the proposed apparatus as an NSM is tested by examining the effects of various geometrical parameters such as guide height, slit width, strip width, distance between slit and strip, and the ratio of slit width to guide height on the magnitude and phase of the voltage reflection coefficient of the TEM wave. From the results for the voltage reflection coefficient against the strip offset from the slit, it is found that a slit in the FPPW with smaller guide height gives higher scanning resolution and the phase variation is more sensitive than the magnitude variation.

키워드

결합, 플랜지된 평행평판도파관, 도체 스트립, 근역장 주사현미경

Key word

Coupling, flanged parallel-plate waveguide(FPPW), conducting strip, near-field scanning microscopy(NSM)

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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 reconsiders a simplified near-field scanning microscope geometry (see Fig. 1) constituted by a flanged parallel-plate waveguide (FPPW) as a probe and a nearby conducting strip parallel to the flanged ground conductor as an object, which was studied in the earlier work [6]. The problem of electromagnetic coupling between the PPW and the outside region through the strip is studied for the case that the TEM mode wave in the PPW is incident on the slit.

In the prior work [6], some numerical results for the reflection coefficient against lateral displacement of strip for various strip-slit distances were presented in order to demonstrate the performance of the structure as an NSM. However, the results were limited to the case of the fixed geometrical parameters, i.e., guide height $h=0.3\lambda_0$ (λ_0 ; wavelength in the free space), slit width $a=10^{-4}\lambda_0$, and strip length $L=10^{-4}\lambda_0$(set equal to the slit width). Moreover, only the magnitude of the voltage reflection coefficient was presented without any discussion about the phase variations although it could not be thought to be unimportant information. Hence, it would be necessary for us to inspect further the geometry as a simplied NSM structure.

In this study, prior to the investigation into the performance of the structure as an NSM, the characteristics of the FPPW itself (without conducting strip) are examined from the variations of equivalent slit admittance, stored reactive powers near the slit inside and outside waveguide, magnitude and phase of the voltage reflection coefficient of the TEM wave against waveguide height with the ratio of slit width to waveguide height as a parameter. The effects of geometrical parameters of the structure such as slit width, strip length, slit-to-strip distance, and waveguide height on the performance of the proposed geometry as an NSM have been investigated. The results demonstrated that a narrow slit in the FPPW with a smaller guide height gives more sensitive change in the phase of the reflection coefficient to the scanning conducting strip, which reveals that high resolution of NSM with this structure is feasible.

II. Theoretical review

Fig. 1 shows a cross-sectional view of a flanged parallel-plate waveguide (FPPW, $z<0$) opening into the half free space ($z>0$) and a conducting strip ($z=Z_0$) parallel to the ground plane ($z=0$). In Fig. 1, h is the guide height, a is the slit width, X_0 is the lateral offset of strip from the origin, L is strip length, and Z_0 is slit-to-strip distance. The y-component of the TEM magnetic field incident on the slit region can be given by

$$H_y^{inc}=\frac{V_{inc}}{\eta h}exp(-jkz) \qquad (1)$$

where, V_{inc} is the potential difference across the plates, k is the wavenumber, and η is the intrinsic impedance of the dielectric ($\mu_0,\epsilon_0\epsilon_r$) inside the FPPW.

Following Butler et al. [7], the present problem can be formulated in terms of coupled integro-differential equations for the induced electric current density $J_x(x)$ on the conducting strip and the magnetic current density

$M_y(x)$, equivalent to the slit electric field $E_x^A(x) \equiv E_x(x,0)$, over the shorted slit. The detailed analysis procedure is given in [6,8-10]. In order to solve the integro-differential equations numerically using moment method, the unknown distributions $J_x(x')$ and $E_x^A(x')$ are expanded in terms of piecewise sinusoidal functions and pulse functions, respectively, and Galerkin's scheme is employed to reduce the equations to a linear form.

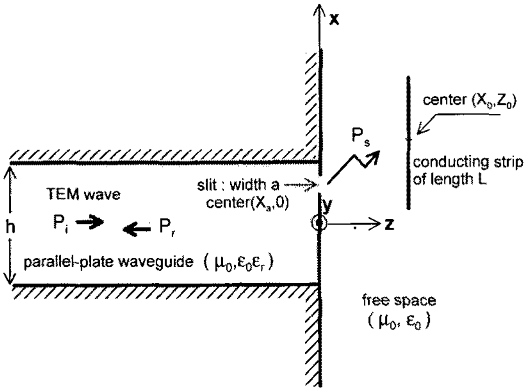


그림 1. 제안된 구조
Fig. 1. Geometry under consideration

From knowledge of the distributions one may obtain all the quantities of interest such as voltage reflection coefficient Γ_V from the slit, the equivalent slit admittance $Y_s(=G_s+jB_s)$, the coupled power P_s through the slit into the exterior free space region, and the stored reactive powers Q_{in} and Q_{ex} in the interior and exterior regions of the slit, respectively [8,9].

The normalized equivalent slit admittance is obtained from the voltage reflection coefficient Γ_V as

$$\begin{aligned} y_s = Y_s/Y_C &= g_s + jb_s = g_s + j(b_{si} + b_{se}) \qquad (2) \\ &= (1-\Gamma_V)/(1+\Gamma_V) \end{aligned}$$

in which $Y_C = 1/\eta h$ is the characteristic admittance of the PPW. The normalized equivalent slit susceptance b_s is associated with the non-propagating reactive fields in the vicinity of the slit and so it could be expressed as the sum of b_{si} and b_{se}, the normalized susceptances on the interior and exterior side of the slit [8,9]. The coupled (radiated) power $P_s(=P_i-P_r)$ through the slit into the free space is related to the normalized conductance g_s. The details are reported elsewhere [8,9].

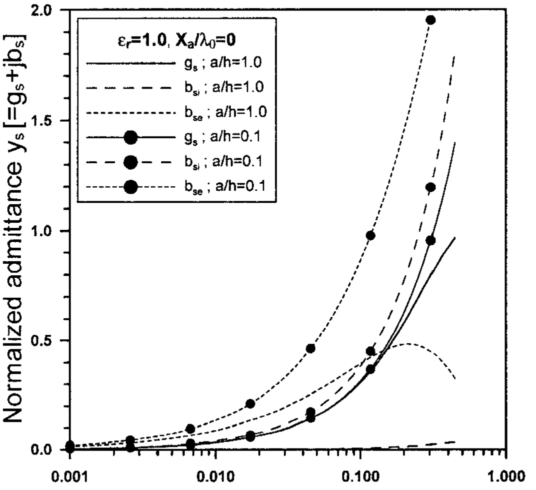
Ⅲ. Results and discussion

Figs. 2a-c show variations of normalized admittance y_s, normalized powers $[p_s(=P_s/P_i),\ q_{in}(=Q_{in}/P_i)$, and $q_{ex}(=Q_{ex}/P_i)]$, and reflection coefficient Γ_V from the slit against the normalized waveguide height (h/λ_0) with the ratio a/h as a parameter. It is seen that for $h \ll \lambda_0$, the normalized conductance (g_s) and susceptance (b_s) are very small (see Fig. 2a) and so the stored reactive powers(Q_{in} and Q_{ex}) as well as the radiated power(P_s) are negligible (see Fig. 2b), indicating that under this condition, most incident power on the slit is reflected and slit behaves as on open circuit (note that the reflection coefficient $\Gamma_V \approx 1\angle 0^\circ$ in Fig. 2c).

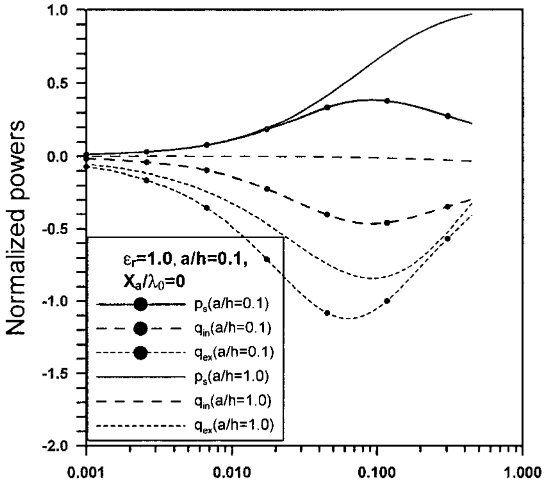
As the waveguide height is increased, the slit no longer behaves as an open circuit and its normalized conductance (g_s) and susceptance b_{se} in the exterior region are increased. The susceptance b_{si} in the interior region remains small value for $a/h=1$ while it increases for $a/h=0.1$. For $a/h=0.1$ in Fig. 2a, the rate of increase in susceptance $b_s(=b_{si}+b_{se})$ is much more than that of conductance g_s, which results in more stored reactive power $Q_s(=Q_{in}+Q_{ex})$ than radiated power P_s, as shown in Fig. 2b. The slit in this case $(a/h=0.1)$ changes from being an open circuit for small h to short circuit $(\Gamma_V = 1\angle -180^\circ)$ when h approaches a half of the free-space wavelength, which is not seen in case of

$a/h = 1$ as shown in Fig. 2c.

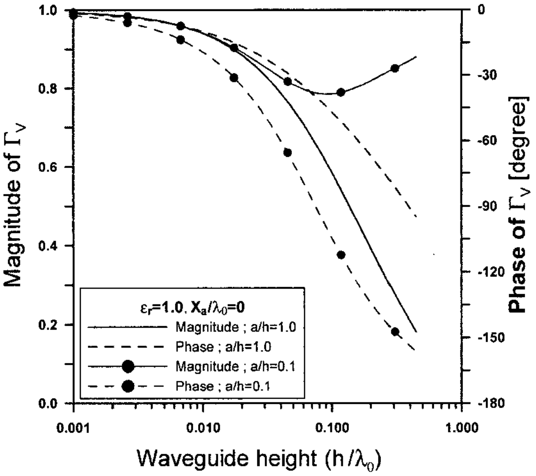
From the results for b_{si} and b_{se} in Fig. 2a, one finds that the reactive power Q_{in} in the waveguide region is much smaller than Q_{ex} in the free space region as far as the ratio a/h is near unity.



(a)



(b)



(c)

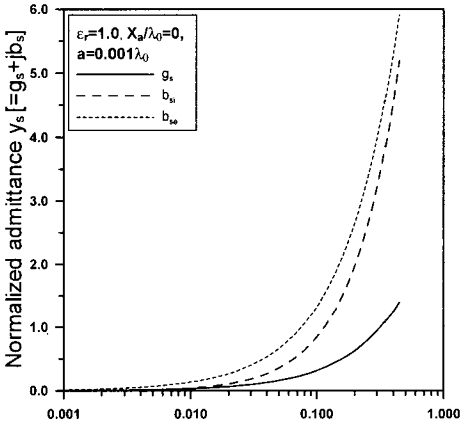
그림 2. 플랜지된 평행평판도파관의 특성
(a) 정규화된 슬릿어드미턴스 $y_s(=g_s+j(b_{si}+b_{se}))$
(b) 정규화된 전력 $p_s(=P_s/P_i)$, $q_{in}(=Q_{in}/P_i)$ 및 $q_{ex}(=Q_{ex}/P_i)$ (c) 전압반사계수 Γ_V

Fig. 2. Characteristics of FPPW (a) Normalized slit admittance $y_s(=g_s+j(b_{si}+b_{se}))$ (b) Normalized powers $p_s(=P_s/P_i)$, $q_{in}(=Q_{in}/P_i)$, and $q_{ex}(=Q_{cx}/P_i)$ (c) Voltage reflection coefficient Γ_V

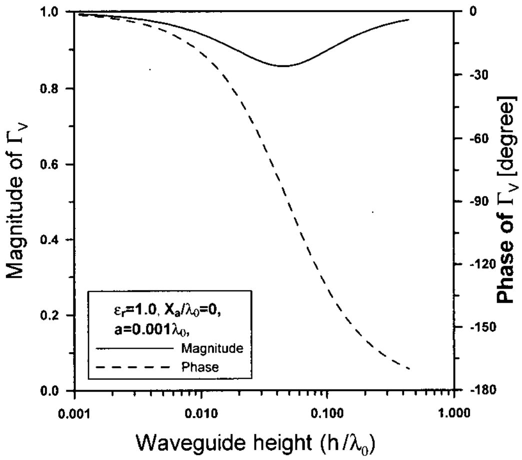
However as the ratio a/h is decreased, the portion of b_{si} as well as the susceptance is increased. As reported in [8], within the limit $ka \to 0$, the susceptance b_s logarithmically approaches to infinity so as to give the voltage reflection coefficient $\Gamma_V = 1\angle -180°$ corresponding to a short circuit. It is worth while to note that for the case of thin waveguide (i.e., $h/\lambda_0 \ll 1$), the susceptance b_{se} is much greater than b_{si}, irrespective of the ratio a/h.

In the above two cases ($a/h = 1.0$ and 0.1) studied, we have varied both a and h maintaining the ratio a/h constant. Next, let's see the effect of variation of only h at a fixed value of $a = 0.001\lambda_0$. The results are shown in Figs. 3a-3c, which show variations of normalized admittance, voltage reflection coefficient (Γ_V), and powers with increasing waveguide height (h) or decreasing a/h. It is seen that as a/h decreases, the normalized conductance and susceptance increase and at very low values of this ratio, the slit behaves as a short circuit resulting in decreased radiated power and stored reactive powers on the interior and exterior side of the slit.

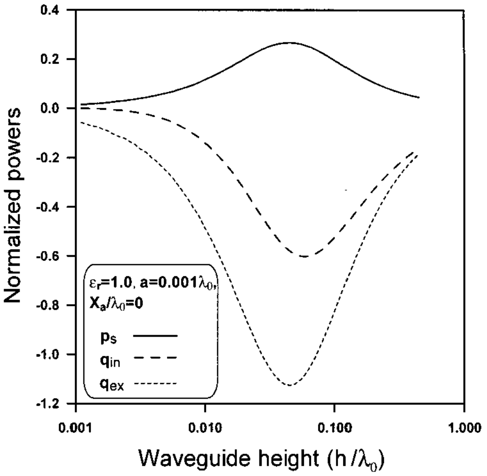
We now test this structure from the viewpoint of near-field scanning microscopy. To do this we place a small conducting strip(i.e., $L/\lambda_0 < 0.1$) at a distance Z_0 from the slit as shown in Fig. 1. We examine the effects of the parameters (Z_0, L, a, and h) on the reflection coefficient from the slit as it is scanned over the strip. Fig. 4 shows the plot of voltage reflection coefficient (Γ_V) against strip offset (X_0/λ_0) for various values of the slit-strip distance (Z_0/λ_0).



(a)



(b)



(c)

그림 3. 플랜지된 평행평판도파관의 특성
(a) 정규화된 슬릿어드미턴스 y_s (b) 전압반사계수 Γ_V
(c) 정규화된 전력 p_s, q_{in} 및 q_{ex}
Fig. 3. Characteristics of FPPW
(a) Normalized slit admittance y_s
(b) Voltage reflection coefficient Γ_V
(c) Normalized powers p_s, q_{in}, and q_{ex}

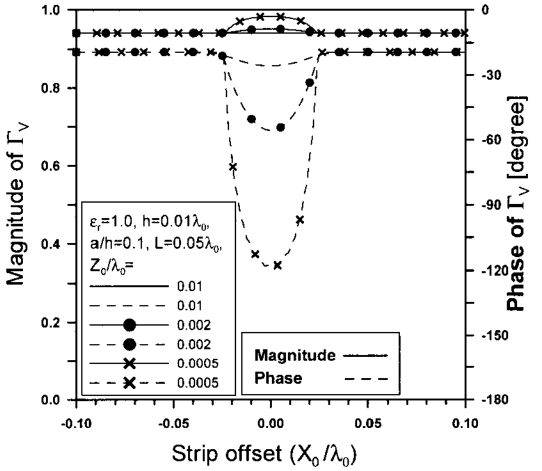


그림 4 거리 Z_0의 영향
Fig. 4. Effect of distance Z_0

It is observed that the change in phase is increased as the distance Z_0 is decreased, while the change in magnitude is not so significant as is seen in the Figure. The phase-change sensitivity is defined as:

$$S = \frac{\Delta\Phi}{\Phi_\infty} \times 100 = \frac{\Phi_0 - \Phi_\infty}{\Phi_\infty} \times 100[\%] \qquad (3)$$

with $\Phi_0 = \angle \Gamma_V(X_0 = 0)$ and $\Phi_\infty = \angle \Gamma_V(X_0 = \infty)$.

As Z_0 is decreased, the relative phase change S is increased, which is obvious since the slit is more effectively shorted as $Z_0 \rightarrow 0$, hence its reflection coefficient Γ_V approaches to $1\angle -180^\circ$. This is true for any value of a/h provided $h \ll \lambda_0$ but when a/h is decreased due to the increase in h, the change S is not so much as in the case of $h \ll \lambda_0$ since slit itself without conducting strip behaves like a short circuit as is observed in Fig. 3c while it behaves like an open circuit for the case of $h \ll \lambda_0$.

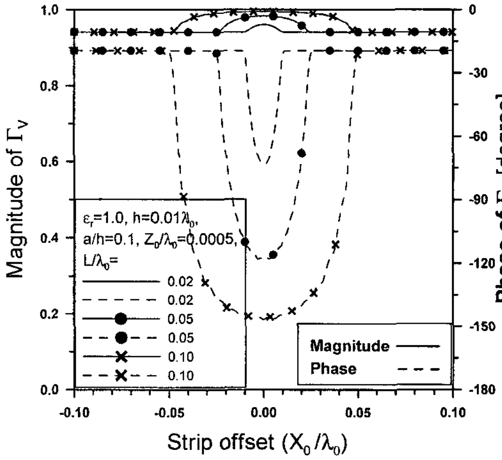


그림 5 스트립폭 L의 영향
Fig. 5. Effect of strip length L

Fig. 5 shows the effect of length (L) of the strip on Γ_V for fixed values of a/h and Z_0. It is seen that with increase in L, the sensitivity S is increased since the slit is more effectively shorted by a longer conducting strip placed near it.

Next, the effect of a/h on Γ_V is shown in Fig. 6 in which a is held constant and h is taken as a parameter. It is seen that a/h affects $\Gamma_V(|X_0| > L/2)$ as well as $\Gamma_V(X_0 = 0)$. In addition, as the offset X_0 is increased (i.e., $|X_0| > L/2$), the reflection coefficient Γ_V approaches fast to that for the case of no strip, i.e., $\Gamma_V(|X_0| > L/2) \approx \Gamma_V(|X_0| = \infty)$.

In order to maximize the sensitivity S, minimization of Φ_∞ as well as maximization of $\Delta\Phi$ is required. The maximization of Φ_0 might be achieved when the slit, due to a conducting strip near it, has been made to be looked as a short circuit ($\Gamma_V = 1\angle -180^\circ$). Then the slit itself without conducting strip should be looked as an open circuit ($\Gamma_V = 1\angle 0^\circ$) so that the sensitivity S might be maximized.

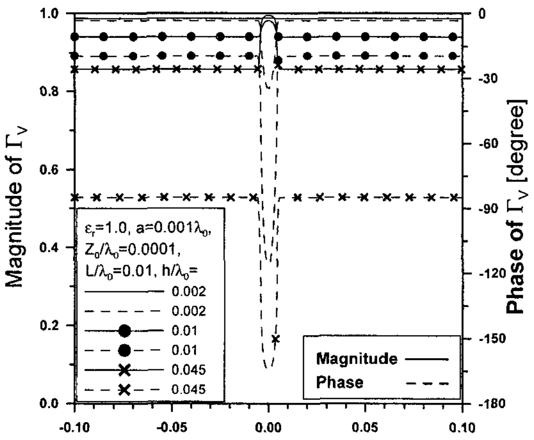


그림 6 a/h의 영향
Fig. 6. Effect of a/h

Fig. 6 shows that Φ_0 becomes close to -180° as a/h is decreased by increasing h while Φ_∞ approaches to 0° as $a/h \rightarrow 1$ owing to the decrease in h. Hence the maximum of S for given slit width a, strip length L, and distance Z_0, as shown in Fig. 6, would be achieved through a tradeoff between the minimization of $|\Phi_\infty|$ and the maximization of $|\Phi_0|$ by adjusting guide height h.

Ⅳ. Conclusion

The problem of electromagnetic coupling through a slit in a flanged parallel-plate waveguide (FPPW) to a conducting strip has been investigated from the viewpoint of a simplified near-field scanning microscopy. From the results for the equivalent slit admittance, complex power, and voltage reflection coefficient, the characteristics of the FPPW itself without conducting strip are examined. The effects of geometrical parameters such as waveguide height, slit width, strip length, and slit-strip distance on the sensitivity of the proposed geometry as a simplified near-field scanning probe of reflection type have been checked. It is found that the FPPW with a smaller guide height gives higher sensitivity in the variations of the phase of the voltage reflection coefficient against the scanning of conducting strip.

References

[1] Y. Gao and I. Wolff, "Miniature electric near-field probes for measuring 3-D fields in planar microwave circuits," *IEEE Trans Microwave Theory Tech.*, vol. 46, pp. 907-913, 1998.

[2] J. M. Vigoureux, F. Depasse, and C. Girard, "Superresolution of near-field optical microscopy defined from properties of confined electromagnetic waves," *Appl Optics,* vol. 31, pp. 3036-3045, 1992.

[3] E. A. Ash and G. N. Nicholls, "Super-resolution aperture scanning microscope," *Nature,* vol. 237, pp. 510-512, 1972.

[4] J. S. Dahele and A. L. Cullen, "Electric probe measurements on microstrip," *IEEE Trans Microwave Theory Tech.,* vol. 28, pp. 752-755, 1980.

[5] S. S. Osofsky and S. E. Schwarz, "A non-contacting probe for measurements on high-frequency planar circuits," *IEEE MTT-S Dig.,* pp. 823-825, 1989.

[6] A. Hochman, P. Paneah, and Y. Leviatan, "Interaction between a waveguide-fed narrow slot and a nearby conducting strip in millimeter-wave scanning microscopy," *J. Appl Phys.,* vol. 88, pp. 5987-5992, 2000.

[7] C. M. Butler et al., "Flanged parallel-plate waveguide coupled to a conducting cylinder," *Proc. IEE, pt. H,* vol. 138, pp. 549-559, 1991.

[8] J. I. Lee, J. H. Ko, and Y. K. Cho, "Coupling through a slit in a flanged parallel-plate waveguide with a conducting strip," *Proc ISAP,* pp. 589-592, 2004.

[9] J. I. Lee, K. W. Kim, and Y. K. Cho, "Equivalent admittance of a slit fed by a flanged parallel-plate waveguide and maximum coupling mechanism through a narrow slit," *JKIEES,* vol. 15, no. 11, pp. 1-8, Nov. 2004.

[10] J. I. Lee and Y. K. Cho, "Maximum coupling phenomena through a slit fed by a flanged parallel-plate waveguide with a conducting strip," *JKIEES,* vol. 17, no. 6, pp. 501-510, June 2006.

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