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외부도체면에 축방향 슬롯이 있는 동축선로 도파관의 산란에 대한 특성모드의 해석 : TE의 경우

(Characteristic modes of a longitudinal slot in the outer conductor of coaxial waveguide for scattering : TE case)

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요 약

임의의 폭을 갖는 축방향 슬롯이 있는 동축선로 도파관의 경우 특성모드 이론을 사용하여 슬롯위에서 특성 자기전류와 등가 자기전류를 구하고, 도파관의 내부, 외부 영역에서 특성 필드, 복사패턴과 총자장을 구하였다. 등가 자기전류와 복사패턴에 대한 수치결과와 모멘트법을 이용하여 구한 결과를 비교하여 이론의 타당성을 보였다.

Abstract

A characteristic mode theory for longitudinal slot of arbitrary width in the outer conductor of coaxial waveguide is applied for calculating the characteristic magnetic currents, the characteristic fields, radiation patterns, and the fields everywhere(inside and outside the guide, and in the aperture region). Numerical results of the equivalent magnetic currents and the radiation patterns are compared with those obtained by use of the method of moments.

I. Introduction

Recently, a characteristic mode theory was developed to treat aperture problems. A general procedure for formulating problems involving electromagnetic coupling through apertures in conducting bodies is given in [1].

Aperture problems concerning the axial slots on circular cylinder have been considered by many previous investigators by use of the characteristic mode formulation[2-3] or dual series formulation[4]. However the corresponding problem of the coaxial waveguide structure has not been reported, from the viewpoint of characteristic mode theory, so far.

In this work, the problem of a longitudinal slot in the outer conductor of coaxial waveguide whose geometry is well suited to the coaxial leaky waveguide is treated using characteristic mode theory when the slot is illuminated by a transverse electric plane wave to the axial slot. The characteristic

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currents obtained are the solution here to an weighted matrix eigenvalue equation representing the continuity of the tangential magnetic field in the longitudinal slot. The equivalent magnetic current in the slot, the characteristic field, the total fields in the internal and external region of the coaxial waveguide are all determined. And numerical results of the equivalent magnetic current are compared with those obtained by use of the conventional method of moments. Good correspondence is observed between them.

Ⅱ. Formulation of the problem

The geometry under consideration is shown in Fig. 1. The axis of the coaxial waveguide is in the z-direction. The inner(outer) radius of coaxial waveguide is a(b) and the coaxial region(region I) is filled with dielectric of relative permittivity ε_r and exterior region (region II) is the free space.

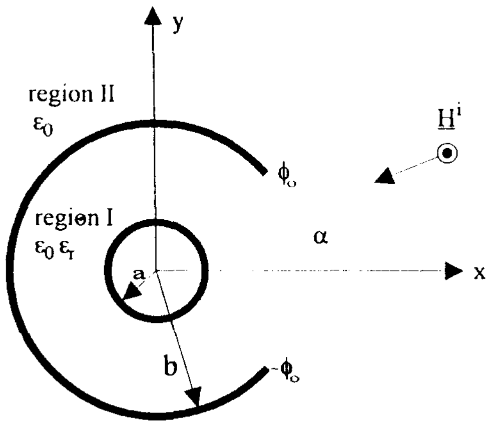


그림 1. 구조 및 좌표계
Fig. 1. Geometry of the problem and coordinate system.

A coaxial waveguide having a longitudinal slot of half angle ϕ_o at $\rho=b$ is illuminated by a TE polarized plane wave. The incident TE wave is assumed to be uniform of unit amplitude and time factor $e^{j\omega t}$ is assumed and suppressed throughout.

In cylindrical coordinate system (ρ,ϕ,z), the incident magnetic field $\underline{H}^i$ is taken to be

$$\underline{H}^i = \hat{z}_o e^{jk_2\rho\cos(\phi-\alpha)} = \hat{z}_o \sum_{n=-\infty}^{\infty} j^n J_n(k_2\rho) e^{jn(\phi-\alpha)} \quad (1)$$

where $\hat{z}_o$ is the unit vector in the z-direction and α is the angle of the direction incoming incident wave and $J_n(\cdot)$ are called Bessel function of order n and $k_2=\omega\sqrt{\mu_o\varepsilon_o}$.

The equivalence principle is used to divide the original problem into two coupled parts. This is accomplished by closing the longitudinal slot with an infinitely thin curved conducting strip and placing the magnetic current $\underline{M}$ on the right-hand side of the closed slot and $-\underline{M}$ on the left-hand side of the closed slot.

To represent outward-traveling waves, the scattered magnetic field by the cylinder without longitudinal slot $\underline{H}^s$ must be of the form

$$\underline{H}^s = \hat{z}_o \sum_{n=-\infty}^{\infty} j^n \Gamma_n H_n^{(2)}(k_2\rho) e^{jn(\phi-\alpha)} \quad (2)$$

where Γ_n is

$$\Gamma_n = -\frac{J_n'(k_2 b)}{H'^{(2)}_n(k_2 b)} \quad (3)$$

and $H_n^{(2)}(\cdot)$ are called Hankel function of second kind of order n and hence the total magnetic field by the cylinder without longitudinal slot is is given by

$$\underline{H}^t = \underline{H}^i + \underline{H}^s = \hat{z}_o \sum_{n=-\infty}^{\infty} j^n \left[J_n(k_2\rho) - \frac{J_n'(k_2 b)}{H'^{(2)}_n(k_2 b)} H_n^{(2)}(k_2\rho) \right] e^{jn(\phi-\alpha)} \quad (4)$$

In the coaxial region $(a<\rho<b)$ the z-component of the magnetic field can be expressed in terms of the equivalent magnetic current at the slot as follows:

$$H_z^I(M_z) = j\frac{k_1 b}{\eta_1} \int_0^{2\pi} M_z(\phi') G_1(\rho,\phi;\rho',\phi') d\phi' \quad (5)$$

where

$$G_1(\rho,\phi;\rho',\phi') = \frac{j}{8}\sum_{n=-\infty}^{\infty}\frac{\Phi_n(k_1\rho)\Phi_n(k_1\rho')}{\Delta} \quad (6)$$

$$\Phi_n(k_1\rho) = H_n^{(1)}(k_1\rho)H'^{(2)}_n(k_1a) - H'^{(1)}_n(k_1a)H_n^{(2)}(k_1\rho) \quad (7)$$

$$\Phi_n(k_1\rho') = H_n^{(1)}(k_1\rho')H'^{(2)}_n(k_1b) - H'^{(1)}_n(k_1b)H_n^{(2)}(k_1\rho') \quad (8)$$

$$\Delta = H'^{(1)}_n(k_1b)H'^{(2)}_n(k_1a) - H'^{(1)}_n(k_1a)H'^{(2)}_n(k_1b) \quad (9)$$

Here $k_1=\omega\sqrt{\mu_o\varepsilon_o\varepsilon_r}$, $\eta_1=120\pi/\sqrt{\varepsilon_r}$, and $H_n^{(1)}$, $H_n^{(2)}$ are the n-th order Hankel functions of the first and second kind respectively and $H'^{(1)}_n(x)=\frac{d}{dx}H_n^{(1)}(x)$.

Similarly, in the exterior region $(\rho>b)$ the z-component of the magnetic field is expressed as

$$H_z^{II}(M_z) = -j\frac{k_2b}{\eta_2}\int_0^{2\pi}M_z(\phi')G_2(\rho,\phi;\rho',\phi')d\phi' \quad (10)$$

,where

$$G_2(\rho,\phi;\rho',\phi') = \frac{j}{8}\sum_{n=-\infty}^{\infty}\frac{H_n^{(2)}(k_2\rho)}{H'^{(2)}_n(k_2b)}\Omega_n(k_2\rho') \quad (11)$$

$$\Omega_n(k_2\rho') = H_n^{(1)}(k_2\rho')H'^{(2)}_n(k_2b) - H'^{(1)}_n(k_2b)H_n^{(2)}(k_2\rho'). \quad (12)$$

The continuity of the magnetic field at the slot ($|\phi|<\phi_0$ and $\rho=b$) requires that

$$H_z^t + H_z^{II}(M_z) = H_z^I(-M_z) \quad , \quad |\phi|<\phi_0. \quad (13)$$

Thus an exact integral equation for the equivalent magnetic current can be obtained from (3), (5), (10), and (13) as follows:

$$-\frac{1}{2\pi j}\sum_{n=-\infty}^{\infty}\left[\frac{1}{\eta_1}\frac{\Phi_n(k_1b)}{\Phi_n'(k_1b)} - \frac{1}{\eta_2}\frac{H_n^{(2)}(k_2b)}{H'^{(2)}_n(k_2b)}\right]\int_0^{2\pi}M_z(\phi')e^{-jn\phi'}d\phi' e^{jn\phi} = \frac{2}{\pi k_2b}\sum_{n=-\infty}^{\infty}\frac{j^{n-1}}{H'^{(2)}_n(k_2b)}e^{jn(\phi-\alpha)} \quad (14)$$

where

$$\Phi_n(k_1b) = H_n^{(1)}(k_1b)H'^{(2)}_n(k_1a) - H'^{(1)}_n(k_1a)H_n^{(2)}(k_1b) \quad (15)$$

$$\Phi_n'(k_1b) = H'^{(1)}_n(k_1b)H'^{(2)}_n(k_1a) - H'^{(1)}_n(k_1a)H'^{(2)}_n(k_1b). \quad (16)$$

This operator equation (14) is written in the form

$$Y(M) = I. \quad (17)$$

The operator Y(M) in (17) is written as the sum of real operator G(M) and imaginary operator jB(M).

One method to solve an operator equation of the form (17) is to obtain a modal solution in terms of eigenfunctions of the operator. These eigenfunctions can be orthogonal with respect to two operators if we introduce a weight operator into the eigenfunction equation. From a property possessed by G, this weight operator must be positive definite. Define a set of eigenfunctions M_m (m=1,2,3,...,L) and let

$$M_z = \sum_{m=1} V_m M_m = \sum \frac{\langle M_m , I\rangle}{1+jb_m} M_m \quad (18)$$

where the coefficients V_m are to be determined and M_m is the m-th characteristic current. Hence, we consider the following generalized eigenvalue equation

$$Y(M_m) = y_m G(M_m) \quad (19)$$

where y_m are eigenvalues and M_m are the eigenfuctions. Let

$$y_m = 1 + jb_m \quad (20)$$

and substitute this and (20) into (19), then the m-th characteristic current M_m satisfies the eigenvalue equation

$$B(M_m) = b_m G(M_m) \quad (21)$$

where b_m are real and $G(M_m)$, $B(M_m)$, and I are given by

$$G(M_m) = \sum_{n=-\infty}^{\infty}\left[\frac{X_n\cos n\phi}{\eta_1} - \frac{Y_n\cos n\phi - Z_n\sin n\phi}{\eta_2}\right]\int_0^{2\pi}M_m(\phi')\cos n\phi' d\phi' + \sum_{n=-\infty}^{\infty}\left[\frac{X_n\sin n\phi}{\eta_1} - \frac{Y_n\sin n\phi + Z_n\cos n\phi}{\eta_2}\right]\int_0^{2\pi}M_m(\phi')\sin n\phi' d\phi' \quad (22)$$

$$B(M_m) = \sum_{n=-\infty}^{\infty}\left[\frac{X_n\sin n\phi}{\eta_1} - \frac{Y_n\sin n\phi + Z_n\cos n\phi}{\eta_2}\right]\int_0^{2\pi}M_m(\phi')\cos n\phi' d\phi' - \sum_{n=-\infty}^{\infty}\left[\frac{X_n\cos n\phi}{\eta_1} - \frac{Y_n\cos n\phi - Z_n\sin n\phi}{\eta_2}\right]\int_0^{2\pi}M_m(\phi')\sin n\phi' d\phi' \quad (23)$$

$$I = \frac{2}{\pi k_2b}\sum_{n=-\infty}^{\infty}\frac{j^{n+1}}{H'^{(2)}_n(k_2b)}e^{jn(\phi-\alpha)}. \quad (24)$$

Here

$$X_n=\frac{J_n'(k_1a)N_n(k_1b)-J_n(k_1b)N_n'(k_1a)}{J_n'(k_1a)N_n'(k_1b)-J_n'(k_1b)N_n'(k_1a)} \quad (25)$$

$$Y_n=\frac{J_n(k_2b)J_n'(k_2b)-N_n(k_2b)N_n'(k_2b)}{J_n'^2(k_2b)+N_n'^2(k_2b)} \quad (26)$$

$$Z_n=\frac{2}{\pi k_2 b}\frac{1}{J_n'^2(k_2b)+N_n'^2(k_2b)}. \quad (27)$$

where $N_n(\cdot)$ are called Bessel function of order n.

To obtain an approximate solution, the m-th characteristic current is expanded as

$$M_m=\sum_{q=1}^{L}U_{mq}f_q \quad (28)$$

where f_q are expansion functions. Substituting (28) into (21) and taking the inner product with each testing function f_p, one obtains the following matrix equation:

$$\sum_{q=1}^{L}U_{mq}\langle f_p, B(f_q)\rangle=b_m\sum_{q=1}^{L}U_{mq}\langle f_p, G(f_q)\rangle, \quad p=1,2,3,\ldots,L. \quad (29)$$

Next, the elements of matrix G and B are defined as follows:

$$\begin{aligned}G_{pq}=&\sum_{n=-\infty}^{\infty}\left[\frac{X_n}{\eta_1}-\frac{Y_n}{\eta_2}\right]\int_0^{2\pi}f_p\cos n\phi\int_0^{2\pi}f_q\cos n\phi'\,d\phi'd\phi\\&-\sum_{n=-\infty}^{\infty}\frac{Z_n}{\eta_2}\int_0^{2\pi}f_p\sin n\phi\int_0^{2\pi}f_q\cos n\phi'\,d\phi'd\phi\\&+\sum_{n=-\infty}^{\infty}\frac{Z_n}{\eta_2}\int_0^{2\pi}f_p\cos n\phi\int_0^{2\pi}f_q\sin n\phi'\,d\phi'd\phi\\&+\sum_{n=-\infty}^{\infty}\left[\frac{X_n}{\eta_1}-\frac{Y_n}{\eta_2}\right]\int_0^{2\pi}f_p\sin n\phi\int_0^{2\pi}f_q\sin n\phi'\,d\phi'd\phi\end{aligned} \quad (30)$$

$$\begin{aligned}B_{pq}=&\sum_{n=-\infty}^{\infty}\frac{Z_n}{\eta_2}\int_0^{2\pi}f_p\cos n\phi\int_0^{2\pi}f_q\cos n\phi'\,d\phi'd\phi\\&+\sum_{n=-\infty}^{\infty}\left[\frac{X_n}{\eta_1}-\frac{Y_n}{\eta_2}\right]\int_0^{2\pi}f_p\sin n\phi\int_0^{2\pi}f_q\cos n\phi'\,d\phi'd\phi\\&-\sum_{n=-\infty}^{\infty}\left[\frac{X_n}{\eta_1}-\frac{Y_n}{\eta_2}\right]\int_0^{2\pi}f_p\cos n\mathrm{phi}\int_0^{2\pi}f_q\sin n\phi'\,d\phi'd\phi\\&+\sum_{n=-\infty}^{\infty}\frac{Z_n}{\eta_2}\int_0^{2\pi}f_p\sin n\phi\int_0^{2\pi}f_q\sin n\phi'\,d\phi'd\phi.\end{aligned} \quad (31)$$

And then Galerkin solution is used, that is, the pulse function is chosen for the testing functions f_p in order to simplify the integration and to satisfy the behavior of the magnetic current at the edge of the slot. These functions are defined as follows:

$$f_p=\begin{cases}1, & \phi_p<\phi<\phi_{p+1}\\0, & \text{elsewhere}\end{cases}. \quad (32)$$

Substituing (32) into (30), (31) and using the odd and even properties of the functions , the pq-th elements of matrices G and B become

$$G_{pq}=\frac{Z_0}{\eta_2}\delta^2+4\sum_{n=1}^{\infty}\frac{Z_n}{\eta_2}\frac{\cos n(\phi_p-\phi_q)(1-\cos n\delta)}{n^2} \quad (33)$$

$$B_{pq}=\left[\frac{X_0}{\eta_1}-\frac{Y_0}{\eta_2}\right]\delta^2+4\sum_{n=1}^{\infty}\left[\frac{X_n}{\eta_1}-\frac{Y_n}{\eta_2}\right]\frac{\cos n(\phi_p-\phi_q)(1-\cos n\delta)}{n^2}. \quad (34)$$

where the angle subtended by each arc is $\delta=2\phi_o/(L-1)$. After computing matrices G and B, b_m and U_{mq} may be obtained. Consecutively from (18), the equivalent magnetic current M_z on the slot is given by

$$M=\frac{2}{\pi k_2 b}\sum_{m=1}^{M}\frac{1}{1+jb_m}\sum_{p=1}^{L}\sum_{q=1}^{L}U_{mp}\left[-\frac{j\delta}{H_1^{(2)}(k_2b)}+4\sum_{n=1}^{\infty}\frac{j^{n+1}}{nH_n^{(2)}(k_2b)}\sin\frac{n\delta}{2}\cos n\left(\phi_p+\frac{\delta}{2}-a\right)\right]U_{mq}f_q. \quad (35)$$

The magnetic fields H_m^{II}, (H_m^{I}) produced by characteristic currents $M_m(-M_m)$ radiating in the environment of region II(I) with the slot short circuited are called characteristic fields of region II(I). The characteristic fields are given by

$$H_m^{I}(M_m)=\frac{1}{2\pi j\eta_1}\sum_{q=1}^{L}X_0U_{mq}\delta+\frac{2}{j\pi\eta_1}\sum_{n=1}^{\infty}\sum_{q=1}^{L}\frac{X_n}{n}U_{mq}\cos n\left(\phi-\phi_q-\frac{\delta}{2}\right)\sin\frac{n\delta}{2} \quad (36)$$

$$H_m^{II}(M_m)=\frac{1}{2\pi j\eta_2}\sum_{q=1}^{L}\frac{H_0^{(2)}(k_2\rho)}{H_0^{(2)}(k_2b)}U_{mq}\delta+\frac{2}{j\pi\eta_2}\sum_{n=1}^{\infty}\sum_{q=1}^{L}\frac{H_n^{(2)}(k_2\rho)}{nH_n^{(2)}(k_2b)}U_{mq}\cos n\left(\phi-\phi_q-\frac{\delta}{2}\right)\sin\frac{n\delta}{2}. \quad (37)$$

The total magnetic fields are then defined as

$$H_z^{I}=\sum_{m=1}^{M}V_mH_m^{I}, \quad 0<\rho<b \quad (38)$$

$$H_z^{II}=\sum_{m=1}^{M}V_mH_m^{II}+H_z^{i}, \quad b<\rho. \quad (39)$$

Here the constants V_m are given in (18), H_z^i is given in (3), and H_m^I and H_m^{II} are given in (36) and (37) respectively.

Ⅲ. Numerical results

The scattering problem by a coaxial waveguide with a longitudinal slot in the outer conductor is solved using the characteristic mode theory when the slot is illuminated by a transverse electric plane wave. The characteristic currents obtained are the solution to an weighted matrix eigenvalue equation representing the continuity of the tangential magnetic field in the longitudinal slot.

After computing the matrices G and B for the case when $\phi_o=30°$, $b=0.05\lambda$, $a=b/2$, $\varepsilon_r=1.6$ the characteristic values b_m and the characteristic currents M_m are obtained. The convergence of the characteristic values b_m is shown in Table I. The convergence of the lower order ones is observed to be faster than those of higher order ones as expected from the study on the axially slotted cylinder[3].

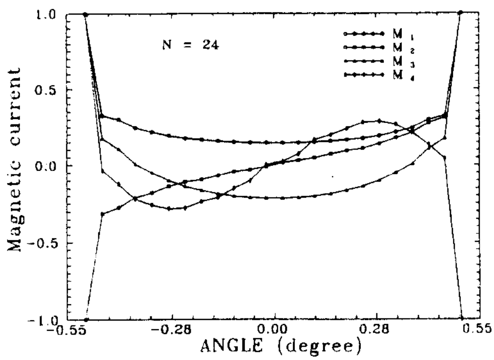


그림 2. $\phi_o=30°$일 때 슬롯에서 4개의 특성전류

Fig. 2. The first four characteristic currents for the slot when $\phi_o=30°$.

표 1. $\phi_o=30°$, $b=0.05\lambda$, $a=b/2$, $\varepsilon_r=1.6$일 때 특성값의 수렴상태

Table 1. Convergence of the characteristic values.($\phi_o=30°$, $b=0.05\lambda$, $a=b/2$, $\varepsilon_r=1.6$)

N	b1	b2	b3	b4	b5
12	-9.7974812	135.6442896	4316.295	1814161.1	91381570.0
16	-9.8192961	134.4093813	4178.826	1714133.1	81817060.0
20	-9.8316644	133.7154868	4137.527	1665478.9	7753310.0
24	09.8410862	133.1893176	4094.796	1633583.1	74974530.0
26	-9.8452497	132.9543291	4076.878	1620639.6	7408380.0
28	-9.8492171	132.7293872	4060.282	1608877.9	73165500.0

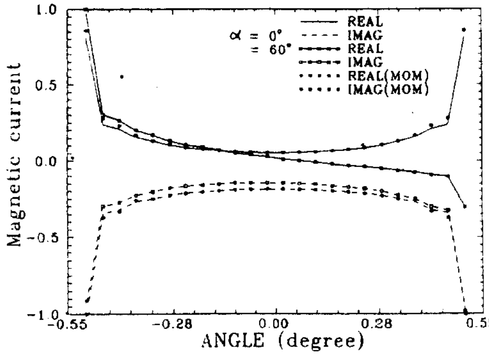


그림 3. $\phi_o=30°$일 때 슬롯에서 등가 자기전류

Fig. 3. The equivalent magnetic currents for the slot when $\phi_o=30°$.

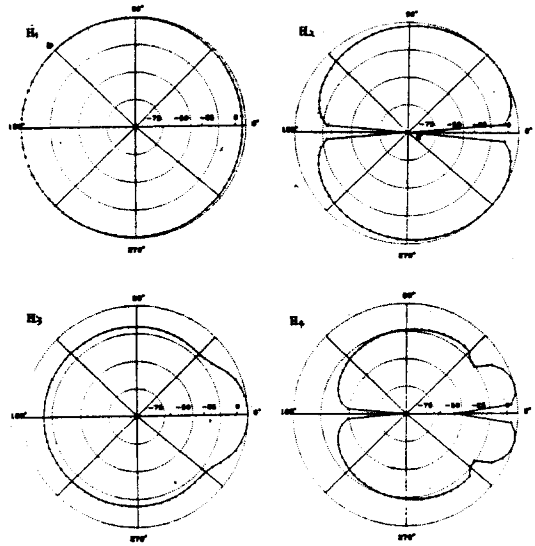


그림 4. $\rho=0.75b$ 이고 $\phi_o=30°$일 때 동축선로 도파관 내부에서 4개의 특성자장

Fig. 4. The first four chracteristic magnetic fields inside the coaxial waveguide when $\rho=0.75b$ and $\phi_o=30°$.

Fig. 2 shows the first four characteristic currents. It is clear from the table that only a limited number of b_m are needed, the first four values in this case, for an accurate solution. These characteristic currents exhibit the even and the odd properties and the proper singular behavior at the edges.

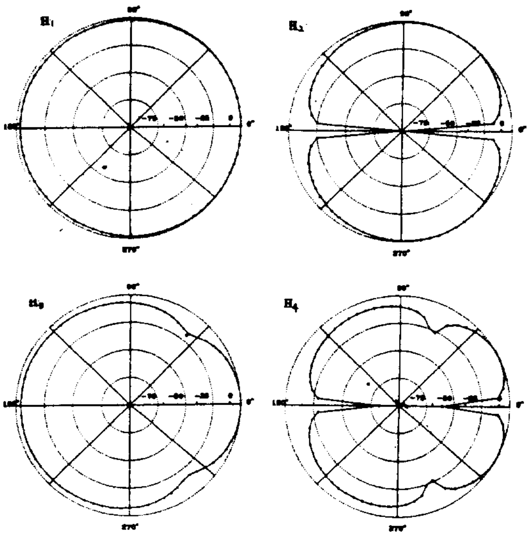
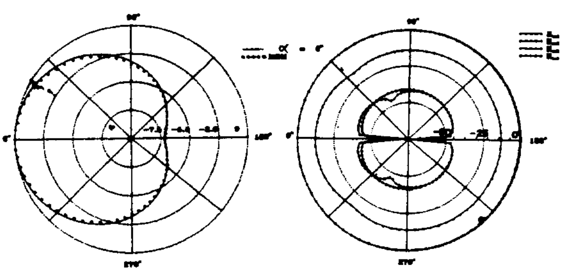


그림 5. $\rho=3$[m] 이고 $\phi_o=30°$일 때 동축선로 도파관 외부에서 4개의 특성자장

Fig. 5. The first four chracteristic magnetic fields outside the coaxial waveguide when $\rho=3$[m] and $\phi_o=30°$.



(a) (b)

그림 6. (a) $\rho=3$[m] , $\alpha=0°$, $\phi_o=30°$일 때 동축선로 외부에서 복사패턴

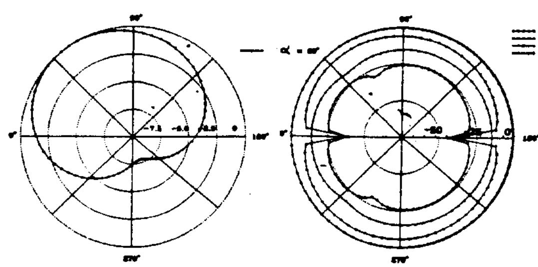
(b) $\rho=3$[m] , $\alpha=0°$, $\phi_o=30°$일 때 동축선로 외부에서 특성자장의 상대적인 크기

Fig. 6. (a) The radiation pattern outside the coaxial waveguide. ($\rho=3$[m] , $\alpha=0°$ and $\phi_o=30°$).

(b) The relative amplitude of the first four characteristic magnetic fields.

In Fig. 3 the equivalent magnetic currents obtained by characteristic mode theory for the case of $\alpha=0°$ and $60°$ are compared with those obtained by use of the MOM. It is seen that two results are in good agreements.

Fig. 4 shows the first four characteristic fields inside the coaxial waveguide at $\rho=0.75b$. Fig. 5 shows the first four characteristic fields outside the coaxial waveguide at $\rho=3$[m] .



(a) (b)

그림 7. (a) $\rho=3$[m] , $\alpha=60°$, $\phi_o=30°$일 때 동축선로 외부에서 복사패턴

(b) $\rho=3$[m] , $\alpha=60°$, $\phi_o=30°$일 때 동축선로 외부에서 특성자장의 상대적인 크기

Fig. 7. (a) The radiation pattern outside the coaxial waveguide. ($\rho=3$[m] , $\alpha=60°$ and $\phi_o=30°$).

(b) The relative amplitude of the first four characteristic magnetic fields.

표 2. $\phi_o=30°$일 때 $|H_z^I|$ 과 $|H_z^{II}|$

Table 2. Fields amplitude $|H_z^I|$ and $|H_z^{II}|$ ($\phi_o=30°$).

α	$\|H_z^I\|$	$\|H_z^{II}\|$
0	0.266	0.268
5	0.263	0.268
10	0.260	0.266

Fig. 6 and 7 show the radiation patterns and characteristic field patterns outside the coaxial waveguide when $\rho=3$[m] for the case of $\alpha=0°$ and $60°$ respectively. It is seen from the Fig. 6b and 7b that relative contributions of higher order modes to the total radiation pattern compared with that of the dominant mode of the first four characteristic fields vary as the incident angle α varies. Table II shows the numerical results for $|H_z|$ over the slot, from which it is seen that the numerical results obtained here satisfy the boundary condition representing the continuity of the tangential magnetic field on the longitudinal slot.

V. Conclusion

The scattering problem by a coaxial waveguide with a longitudinal slot in the outer conductor whose geometry is well suited to the leaky coaxial waveguide is treated using characteristic mode theory when the slot is illuminated by a TE plane wave to the slot. Numerical results for the equivalent magnetic currents and radiation patterns are compared with those obtained by use of the conventional method of moments in order to check the validity of the results. Good correspondence has been observed between them.

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