Radiation Characteristics of Finite Strip-Grating Loaded Dielectric-Coated Coaxial Waveguide with Finite Periodic Thick Slots

Joong-Pyo Kim[1] · Chang-Won Lee[2]

Abstract

The radiation characteristics of leaky wave emanated from finite strip-grating loaded dielectric coated coaxial waveguide with finite periodic thick slots are investigated theoretically. The rigorous integral equations are derived for the proposed structure using the Fourier transform, mode expansion, and sine series expansion of the electric current on metallic strips, and the simultaneous linear equations are obtained. The effects of finite strip-grating loading on a dielectric-coated coaxial waveguide with finite periodic thick slots are examined in terms of radiation characteristics.

Key words : coaxial waveguide, leaky wave antenna, periodic structure, strip-grating

Ⅰ. Introduction

The millimeter-wave omnidirectional leaky-wave antenna has been a subject of several investigations because of an increasing need for developing new antenna types to suit the various demands imposed by the millimeter-wave systems. A circular dielectric waveguide with periodic corrugations[1] and a metallic grating loaded circular dielectric waveguide[2] were investigated theoretically and experimentally to produce an omnidirectional leaky wave antenna. The leakage constant of the former structure was so small that a long antenna length was required to obtain reasonable antenna efficiency. Thus, the latter structure allowing a larger leakage constant was proposed to reduce the antenna length. Both structures must have the transducer between excitation circular waveguide and feeder section to obtain a circularly symmetrical incident field feeding into the radiator. Recently, a new omnidirectional leaky wave antenna, i.e., a dielectric-coated coaxial waveguide periodic slot was proposed and analyzed to obtain a simpler feeding structure and improve the performance of leaky wave antenna [3].

In this paper, to control the leakage constant of the leaky wave antenna presented in [3], a finite strip-grating are loaded on dielectric-coated coaxial waveguide with finite periodic thick slots. In order to obtain a rigorous solution for the proposed structure, we employed the radial waveguide TM modes in slot regions, the inverse Fourier transform in the spectral domain for the other regions, and the sine series expansion of the electric current on strips. The boundary conditions at the interfaces are imposed and the simultaneous linear equations are derived.

The influences of finite strip-grating loading on the leaky-wave radiation characteristics are investigated. It is found that the proper strip loading can make the leakage constant larger than no strip loading case[3], thus enhance the radiation efficiency and reduce the antenna length in terms of the antenna efficiency.

Ⅱ. Formulation

A dielectric-coated coaxial waveguide with K periodic finite thick slots, being loaded with J periodic finite strip-gratings is shown in Fig. 1. It is assumed that TEM mode is incident in the coaxial waveguide and (b − a) is small enough that only TEM mode is the propagating mode in the coaxial waveguide. The

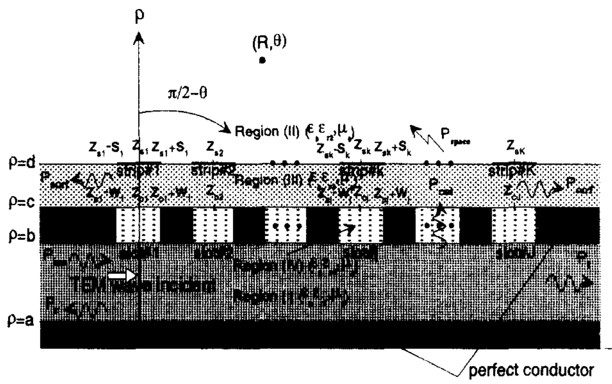

Fig. 1. Geometry of the proposed antenna.

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incident field is

$$H_\phi^{i(I)}(\rho,z)=\frac{Vk_1}{\omega\mu_0\ln(b/a)\rho}e^{-jk_1z}, \tag{1}$$

The scattered field in region (I) which satisfies the boundary condition at $\rho=a$ is expressed as

$$H_\phi^{s(I)}(\rho,z)=\frac{1}{2\pi}\int_{-\infty}^{\infty}\tilde{H}_\phi^{s(I)}(\zeta)\left[H_1^{(2)}(k_{\rho1}\rho)-\frac{H_0^{(2)}(k_{\rho1}a)}{H_0^{(1)}(k_{\rho1}a)}H_1^{(1)}(k_{\rho1}\rho)\right]e^{-j\zeta z}d\zeta \tag{2}$$

where $k_{\rho1}=\sqrt{k_1^2-\zeta^2}$, $H_n^{(1)}(\cdot)$ is the n order Hankel function of the first kind. In region (II), the field is expressed as a superposition of outgoing waves in the ρ direction

$$H_\phi^{(II)}(\rho,z)=\frac{1}{2\pi}\int_{-\infty}^{\infty}\tilde{H}_\phi^{(II)}(\zeta)H_1^{(2)}(k_{\rho2}\rho)e^{-j\zeta z}d\zeta, \tag{3}$$

where $k_{\rho2}=\sqrt{k_2^2-\zeta^2}$. In region (III), the field is represented as a superposition of standing wave in the ρ direction

$$H_\phi^{(III)}(\rho,z)=\frac{1}{2\pi}\int_{-\infty}^{\infty}[\tilde{H}_\phi^{(III)^+}(\zeta)H_1^{(2)}(k_{\rho2}\rho)+\tilde{H}_\phi^{(III)^-}(\zeta)H_1^{(1)}(k_{\rho2}\rho)]e^{-j\zeta z}d\zeta, \tag{4}$$

where $k_{\rho3}=\sqrt{k_3^2-\zeta^2}$.

In region (IV), the field in the l-th slot can be expressed as a summation of radial waveguide TM modes

$$H_\phi^{(IV)}(\rho,z)=\sum_{m=0}^{\infty}C_m^l\cos\omega_m^l(z-z_{cl}+w_l)\times\left[B_m^l\frac{H_1^{(1)}(k_{\rho4m}^l\rho)}{H_1^{(1)}(k_{\rho4m}^lc)}+C_m^l\frac{H_1^{(2)}(k_{\rho4m}^l\rho)}{H_1^{(2)}(k_{\rho4m}^lb)}\right], \tag{5}$$

where $k_{\rho4m}^l=\sqrt{k_4^2-{\omega_m^l}^2}$, $\omega_m^l=m\pi/2w_l$.

The boundary conditions will be imposed at every interface are given as

$$E_z^{s(I)}(b,z)=\begin{cases}E_z^{(IV)}(b,z), & |z-z_{cl}|\le w_l,\ l=1,2,\cdots,J\\ 0, & \text{otherwise}\end{cases}, \tag{6}$$

$$H_\phi^{i(I)}(b,z)+H_\phi^{s(I)}(b,z)=H_\phi^{(IV)}(b,z),\ |z-z_{cl}|\le w_l, \tag{7}$$

$$E_z^{(II)}(d,z)=E_z^{(III)}(d,z),\quad |z|\le\infty \tag{8}$$

$$H_\phi^{(II)}(d,z)-H_\phi^{(III)}(d,z)=\begin{cases}J_z^k(z), |z-z_{sk}|\le s_k,\ k=1,2,\cdots,K\\ 0, \quad \text{otherwise}\end{cases}, \tag{9}$$

$$E_z^{(II)}(d,z)=0,\ |z-z_{sk}|\le s_k,\ k=1,2,\cdots,K \tag{10}$$

$$E_z^{(III)}(c,z)=\begin{cases}E_z^{(IV)}(c,z), & |z-z_{cl}|\le w_l\\ 0, & \text{otherwise}\end{cases}, \tag{11}$$

$$H_\phi^{(III)}(c,z)=H_\phi^{(IV)}(c,z),\ |z-z_{cl}|\le w_l,\ l=1,2,\cdots,J. \tag{12}$$

where the unknown strip electric current $J_z^k(z)$ is expanded into a series of sine functions considering edge behavior as

$$J_z^k(z)=\sum_{m=1}^{\infty}A_m^k\sin a_m^k(z-z_{sk}+s_k), \tag{13}$$

where $a_m^k=m\pi/2s_k$. After imposing the boundary conditions, we can derive the following equations

$$\sum_{l=1}^{J}\sum_{m=0}^{\infty}\frac{\varepsilon_{r2}k_{\rho4m}}{2\pi\varepsilon_{r4}}N_m^l(b)H_{nm}^{rl}-\left[B_n^r\frac{H_1^{(1)}(k_{\rho4n}^rb)}{H_1^{(1)}(k_{\rho4n}^rc)}+C_n^r\right]\alpha_nw_r=-\frac{Vk_1}{k_0\eta_0\ln(b/a)b}P_n^r(-k_1) \tag{14}$$

$$\sum_{k=1}^{K}\sum_{m=1}^{\infty}A_m^ka_m^ka_n^j\frac{-1}{2\pi}I_{nm}^{jk}+\sum_{l=1}^{J}\sum_{m=0}^{\infty}a_n^j\frac{k_{\rho4m}^l}{2\pi\varepsilon_{r4}}N_m^l(c)J_{nm}^{jk}=0, \tag{15}$$

$$\sum_{k=1}^{K}\sum_{m=1}^{\infty}A_m^ka_m^k\frac{-1}{2\pi}J_{nm}^{rk}+\sum_{l=1}^{J}\sum_{m=0}^{\infty}a_n^j\frac{\varepsilon_{r3}k_{\rho4m}^l}{2\pi\varepsilon_{r4}}N_m^l(c)K_{nm}^{rk}-\left[B_n^r+C_n^r\frac{H_1^{(2)}(k_{\rho4n}^rc)}{H_1^{(2)}(k_{\rho4n}^rb)}\right]\alpha_nw_r=0, \tag{16}$$

where $N_m^l(\rho)=B_m^l\frac{H_0^{(1)}(k_{\rho4m}^l\rho)}{H_1^{(1)}(k_{\rho4m}^lc)}+C_m^l\frac{H_0^{(2)}(k_{\rho4m}^l\rho)}{H_1^{(2)}(k_{\rho4m}^lb)}$,

H_{nm}^{rl} and K_{nm}^{rl} are given in [3], and I_{nm}^{jk}, J_{nm}^{jl} and J_{nm}^{rk} are represented as

$$I_{nm}^{jk}=\int_{-\infty}^{\infty}\frac{k_{\rho2}k_{\rho3}H_0^{(2)}(k_{\rho2}d)[H_0^{(1)}(k_{\rho3}c)H_0^{(2)}(k_{\rho3}d)-H_0^{(2)}(k_{\rho3}c)H_0^{(1)}(k_{\rho3}d)]}{[M^+(\zeta)H_0^{(2)}(k_{\rho3}c)-M^-(\zeta)H_0^{(1)}(k_{\rho3}c)]}\cdot Q_m^k(\zeta)Q_n^j(-\zeta)d\zeta,$$

$$J_{nm}^{jl}=\int_{-\infty}^{\infty}\frac{\varepsilon_{r3}k_{\rho2}H_0^{(2)}(k_{\rho2}d)[H_0^{(1)}(k_{\rho3}d)H_1^{(2)}(k_{\rho3}d)-H_0^{(2)}(k_{\rho3}d)H_1^{(1)}(k_{\rho3}d)]}{[M^+(\zeta)H_0^{(2)}(k_{\rho3}c)-M^-(\zeta)H_0^{(1)}(k_{\rho3}c)]}\cdot P_m^l(\zeta)Q_n^j(-\zeta)d\zeta,$$

$$J_{nm}^{rk}=\int_{-\infty}^{\infty}\frac{\varepsilon_{r3}k_{\rho2}H_0^{(2)}(k_{\rho2}d)[H_0^{(1)}(k_{\rho3}c)H_1^{(2)}(k_{\rho3}c)-H_0^{(2)}(k_{\rho3}c)H_1^{(1)}(k_{\rho3}c)]}{[M^+(\zeta)H_0^{(2)}(k_{\rho3}c)-M^-(\zeta)H_0^{(1)}(k_{\rho3}c)]}\cdot Q_m^k(\zeta)P_n^r(-\zeta)d\zeta,$$

where *

$$M^+(\zeta)=\varepsilon_{r2}k_{\rho3}H_0^{(1)}(k_{\rho3}d)H_1^{(2)}(k_{\rho2}d)-\varepsilon_{r3}k_{\rho2}H_1^{(1)}(k_{\rho3}d)H_0^{(2)}(k_{\rho2}d)],$$

$$M^-(\zeta)=\varepsilon_{r2}k_{\rho3}H_0^{(2)}(k_{\rho3}d)H_1^{(2)}(k_{\rho2}d)-\varepsilon_{r3}k_{\rho2}H_1^{(2)}(k_{\rho3}d)H_0^{(2)}(k_{\rho2}d)],$$

$$Q_u^v(\zeta)=\frac{[(-1)^ue^{j\zeta s_v}-e^{-j\zeta s_v}]e^{j\zeta z_{sv}}}{\zeta^2-a_u^v},\ u=m,n,\ v=k,j,$$

$$P_u^v(\zeta)=\frac{-j\zeta[(-1)^ue^{j\zeta w_v}-e^{-j\zeta w_v}]e^{j\zeta z_{cv}}}{\zeta^2-\omega_u^v},\ u=m,n,\ v=k,j.$$

Using (14)~(16), we can obtain the following simultaneous equations

$$\begin{bmatrix} \Psi_1 & \Psi_2 & \Psi_3 \\ \Psi_4 & \Psi_5 & \Psi_6 \\ \Psi_7 & \Psi_8 & \Psi_9 \end{bmatrix} \begin{bmatrix} A \\ B \\ C \end{bmatrix} = \begin{bmatrix} S \\ 0 \\ 0 \end{bmatrix}. \tag{17}$$

Once the unknown mode coefficients A_m^k, B_m^l and C_m^l are determined by solving (17), $\tilde{H}_\phi^{s(I)}$, $\tilde{H}_\phi^{(II)}$, $\tilde{H}_\phi^{(III)+}$ and $\tilde{H}_\phi^{(III)-}$ are computed. Hence, the fields in each region can be calculated. The wave radiated from the slots are divided into two wave types, i.e., one is the space wave which is radiated into the region (II), and the other the surface wave which is trapped in and above the dielectric and guided in the $\pm z$ directions. The far-zone magnetic field radiated into the region (II) as space wave is calculated by using an asymptotic evaluation while the surface wave in each region calculated by applying the Cauchy residue theorem.

The time-averaged incident power (P_{inc}) is divided into the reflected power (P_r), the coupled power to the guide beyond the slotted region (P_t), and the transmitted power from slots (P_{rad}) to regions (II) and (III), and also P_{rad} is divided into the space wave power (P_{space}) and the surface wave power (P_{surf}).

Ⅲ. Numerical Results

The validity of the numerical results in this paper is assured by a check of the power conservation law

$$P_{inc} = P_r + P_t + P_{rad},$$
$$P_{rad} = P_{space} + P_{surf}.$$

In order to investigate the effects of strip-grating loading on the dielectric-coated coaxial waveguide with finite periodic thick slots[3], we put the slot and strip period as Tc and Ts, respectively, for all examples below. The variation of the normalized powers, radiation angle and beamwidth versus the strip width as a parameter is shown in Fig. 2 and Fig. 3, when the number of strip is 40. Fig. 2 shows that the power conservation law is very well satisfied for all strip widths. The normalized powers, radiation angle and beamwidth are approaching to the values of no strip loading case[3] as the strip width decreases to zero. As the strip width increases, the leakage constant increases by electromagnetic coupling through the slots to the strips, so the radiated power will be gradually increased. Fig. 2 and 3 show that the radiated power is maximum at the point of $2s=0.4T_s$ and about 7 % larger than that of no strip loading case[3], while the beamwidth slightly increases and the radiation angle decreases compared to [3]. And after that point the radiated power decreases and the reflected power increases and the beamwidth rapidly increases, due to the

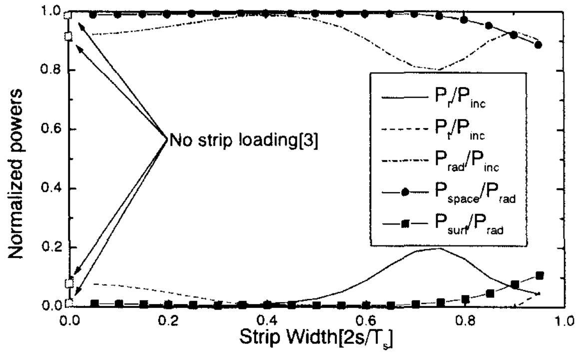

Fig. 2. Normalized powers versus the strip width: $T_c = 0.55\lambda$, $T_s = 0.55\lambda$, $a = 0.05\lambda$, $b = 0.25\lambda$, $c = 0.3\lambda$, $d = 0.4\lambda$, $w = 0.25T_c$, $\varepsilon_{r1} = 2.5$, $\varepsilon_{r2} = 1.0$, $\varepsilon_{r3} = \varepsilon_{r4} = 2.0$.

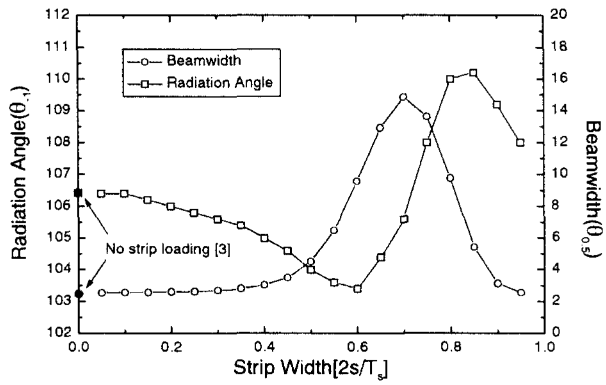

Fig. 3. Radiation angle and beamwidth versus the strip width: $T_c=0.55\lambda$, $T_s=0.55\lambda$, $a=0.05\lambda$, $b=0.25\lambda$, $c=0.3\lambda$, $d=0.4\lambda$, $w=0.25T_c$, $\varepsilon_{r1} = 2.5$, $\varepsilon_{r2} = 1.0$, $\varepsilon_{r3} = \varepsilon_{r4} = 2.0$.

blocking effect of the strips on the coupling of the guided wave in the coaxial waveguide to the space wave in region (II). For the larger strip width than $0.6T_s$, it is found that the strip loading degrades the antenna performances (the antenna efficiency and beamwidth). From this, we can conclude that the optimum strip width is about $0.35T_s$.

Fig. 4 shows the variation of the powers versus the strip number when this optimum strip width ($2s= 0.35\,T_s$) is used. This figure shows that for the same slot number, the radiated power is larger than that of no strip loading case (shown in Fig. 8 in [3]). For example, in the case of 20 slots, the radiated power of the strip loading case is 18 % larger than that of no strip loading case. This result shows that the antenna length can be shortened as many as 10 slot periods in terms of antenna efficiency compared to no strip loading case[3].

The variation of the radiation angle and beamwidth versus thenumber of strip is shown in Fig. 5. The radiation angle and

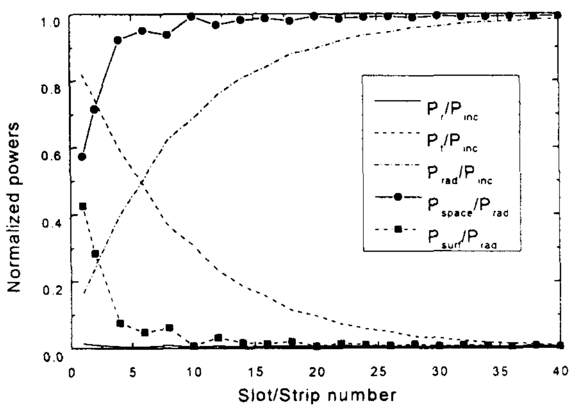

Fig. 4. Normalized powers versus the strip number: $T_c=0.55\lambda$, T_s=0.55 λ, a=0.05 λ, b=0.25 λ, c=0.3 λ, d=0.4 λ, w=0.25T_c, s=0.175T_s, ε_{r1} = 2.5, ε_{r2} = 1.0, $\varepsilon_{r3} = \varepsilon_{r4}$ = 2.0.

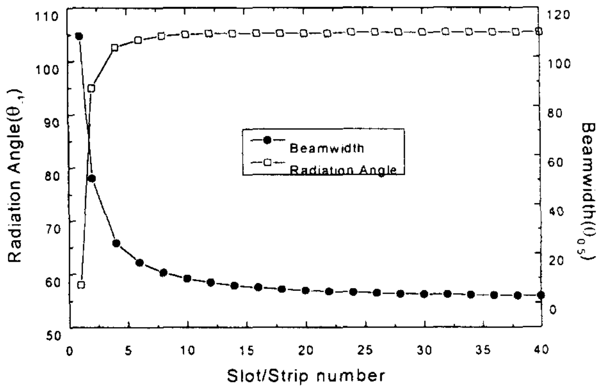

Fig. 5. Radiation angle and beamwidth versus the strip number: $T_c=0.55\lambda$, T_s=0.55 λ, a=0.05 λ, b=0.25 λ, c=0.3 λ, d=0.4 λ, w=0.25Tc, s=0.175Ts, ε_{r1} = 2.5, ε_{r2} = 1.0, $\varepsilon_{r3} = \varepsilon_{r4}$=2.0.

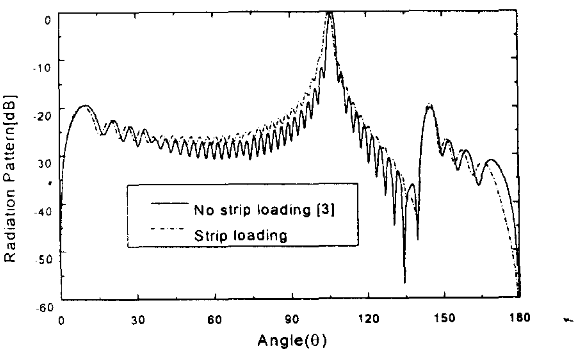

Fig. 6. Radiation pattern: T_c=0.55 λ, T_s=0.55 λ, a=0.05 λ, b=0.25 λ, c=0.3 λ, d=0.4 λ, w=0.25T_c, s=0.175T_s, ε_{r1} =2.5, ε_{r2} =1.0, $\varepsilon_{r3} = \varepsilon_{r4}$=2.0.

beamwidth are converged to almost constant values when the strip number is larger than 20.

Fig. 6 shows the radiation pattern of the strip loading case compared to that of no strip loading case[3]. The main beam radiation angle and beamwidth of strip loading case are 105.4 ° and 2.8 °, respectively while those of no strip loading case are 106.4 ° and 2.6 °. We can find that by the strip loading the antenna efficiency is improved(about 7 %), but the radiation angle and beamwidth are almost not changed.

Ⅳ. Conclusion

The rigorous analysis method for the leaky wave radiated from the finite strip-grating loaded dielectric-coated coaxial waveguide with finite periodic thick slots is proposed. The validity of the proposed method is assured by the power conservation law and also checked by the radiation characteristics in a limiting case where the strip width is decreased to zero. It has been found that the strip-grating loading on the dielectric coated coaxial waveguide with finite periodic thick slots can enhance the radiation efficiency, when compared with the case of no strip-grating loading, and as the result of it, the antenna length can be reduced with almost same antenna efficiency.

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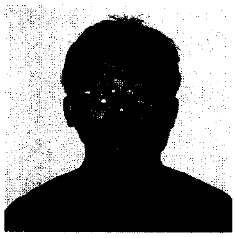

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