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Analysis of Electromagnetic Scattering by a Resistive Strip Grating with Tapered Resistivity on Dielectric Multilayers

다층 유전체위의 변하는 저항율을 가진 저항띠 격자구조에 의한 전자파 산란 해석

Uei-Joong Yoon

尹 義 重

요 약

본 논문에서는 3개의 유전체층 위의 변하는 저항율을 가진 저항띠 격자구조에 의한 E-분극 전자파 산란 문제들은 Fourier-Galerkin 모멘트 법을 이용하여 저항띠의 변하는 저항율과 3개의 유전체 층의 비유전율 및 두께에 대한 효과를 알기 위해 해석하였다. 유도되는 표면전류는 차수 $\alpha=0$과 $\beta=1$의 값을 가지는 직교다항식의 일종인 Jacobi-polynomial $P_p^{(\alpha,\beta)}(\cdot)$의 급수로 전개하였으며, 저항띠의 변하는 저항율은 한쪽 모서리에서는 0이고 다른 쪽 모서리로 가면서 유한한 값으로 선형적으로 변하는 것으로 가정하였다. 정규화된 반사 및 투과전력은 저항띠의 변하는 저항율과 유전체 층들의 비유전율 및 두께를 변화시켜 얻었다. 급변점들은 전파모드와 감쇠모드사이에서 고차모드가 모드 전환될 때 관측되었으며, 전반적으로 국부적인 최소점들은 유전체 층들의 비유전율이 증가함에 따라 격자주기가 작아지는 값에서 발생하였다. 변하는 저하율에 따른 정규화된 반사전력 및 투과전력의 패턴은 균일 저하율 및 완전도체 경우와 매우 다르다는 것이 주목된다. 본 논문의 제안된 방법은 변하는 저항율, 균일 저항율 및 완전도체 띠들의 경우에 대한 산란문제들을 해결할 수 있다.

Abstract

In this paper, the E-polarized electromagnetic scattering problems by a resistive strip grating with tapered resistivity on 3 dielectric layers are analyzed to find out the effects for the tapered resistivity of resistive strips and the relative permittivity and thickness of 3 dielectric layers by applying the Fourier-Galerkin moment methods. The induced surface current density is expanded in a series of Jacobi-polynomial $P_p^{(\alpha,\beta)}(\cdot)$ of the order $\alpha=0$ and $\beta=1$ as a kind of orthogonal polynomials, and the tapered resistivity assumes to vary linearly from 0 at one edge to finite resistivity at the other edge. The normalized reflected and transmitted powers are obtained by varying the tapered resistivity and the relative permittivity and thickness of dielectric layers. The sharp variation points are observed when the higher order modes are transferred between propagating and evanescent modes, and in general the local minimum positions occur at less grating period for the more relative permittivity of di-

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electric layers. It should be noted that the patterns of the normalized reflected and transmitted powers for the tapered resistivity are very much different from those of the uniform resistivity and perfectly conducting cases. The proposed method of this paper can solve the scattering problems for the tapered resistive, uniform resistive, and PEC strip cases.

Ⅰ. Introduction

Scattering properties of the array of conducting strips in free space or on dielectric slabs have been gathering attention in the fields of optics and electromagnetics. Many analytical and numerical methods have been devised and employed to determine these properties.

Richmond[1] added edge mode (to take care of the singularities) to the Fourier series for the unknown current density expansion on perfectly conducting (PEC) strips, and then used the Fourier-Galerkin moment methods (FGMM). The scattering problems from a periodic array of resistive strips were analyzed by using the spectral-Galerkin moment method (SGMM)[2],[3] and the FGMM[4], respectively. Electromagnetic scattering problems by a PEC strip grating over a grounded dielectric layer were analyzed by using the point matching method (PMM)[5] and the FGMM[6],[7] respectively. Volakis et al.[8] considered TE-characterization of resistive strip gratings on a dielectric slab using a single edge-mode expansion. Yoon and Yang[9] analyzed the scattering problem by a perfectly conducting strip grating on dielectric multilayers.

In this paper, we solved numerically the E-polarized scattering problems by a resistive strip grating with tapered resistivity on 3 dielectric layers by using FGMM, and the purpose of this paper is to find out the effects for the relative permittivity and thickness of dielectric layers and the tapered resistivity of resistive strips on 3 dielectric layers. The induced surface current density is expanded in a series of Jacobi-polynomial $P_p^{(\alpha,\beta)}(\cdot)$ of the order $\alpha=0$ and $\beta=1$ as a kind of orthogonal polynomial[10], and the tapered resistivity assumes to vary linearly from 0 at one edge to finite resistivity at the other edge. We apply the continuity to the electromagnetic fields in boundary planes to obtain the unknown coefficients, and the resistive boundary condition is used for the relation between the total tangential electric field and the electric current density on the resistive strips. The numerical results for the normalized reflected and transmitted powers are compared with those of the existing papers, and the resistive strips assume to have infinitesimal thickness.

Ⅱ. Formulation of the Problem

We consider the periodic array of thin resistive strip with tapered resistivity on 3 dielectric layers illuminated by a E-polarized plane wave. Fig. 1 shows the cross section of the resistive strip grating which are uniform in the y direction. E-polarized plane wave with its electric vector parallel to the edge of the resistive strip gratings is incident at arbitrary angle ϕ. The regions 1 and 5 are free space, the regions 2, 3, and 4 are dielectric layers,

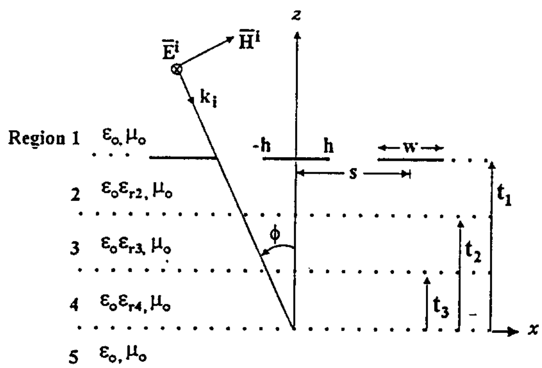

Fig. 1. Geometry of the problem.

the relative permittivities of the dielectric layers 2, 3, and 4 are ε_{r2}, ε_{r3}, and ε_{r4}, respectively.

The incident electric field $\overline{E^i}$ and scattered electric field $\overline{E^s}$ and total electric field $\overline{E^t_2}$, $\overline{E^t_3}$, $\overline{E^t_4}$, $\overline{E^t_5}$ in the regions 2, 3, 4, and 5 can be written as[9]

$$\overline{E^i} = \hat{a}_y\ E_0\, e^{-jk_0 x\sin\phi}\, e^{jk_0 z\cos\phi} \tag{1}$$

$$\overline{E^s} = \hat{a}_y\ E_0\, e^{-jk_0 x\sin\phi} \sum_{n=-\infty}^{\infty} A_n\, e^{-j\gamma_n(z-t_1)}\, e^{-j2n\pi x/s} \tag{2}$$

$$\gamma_n = \begin{cases} \sqrt{k_0^2-\beta_n^2}, & k_0^2 \ge \beta_n^2 \\ -j\sqrt{\beta_n^2-k_0^2}, & k_0^2 < \beta_n^2 \end{cases} \tag{3}$$

$$\overline{E^t_i} = \hat{a}_y\ E_0\, e^{-jk_0 x\sin\phi} \sum_{n=-\infty}^{\infty} \left[B_{ni} e^{-j\eta_{ni} z} + C_{ni} e^{j\eta_{ni} z}\right] e^{-j2n\pi x/s} \tag{4}$$

$$\eta_{ni} = \begin{cases} \sqrt{k_i^2-\beta_n^2}, & k_i^2 \ge \beta_n^2 \\ -j\sqrt{\beta_n^2-k_i^2}, & k_i^2 < \beta_n^2 \end{cases},\ i = 2,\ 3,\ 4 \tag{5}$$

$$\overline{E^t_5} = \hat{a}_y\ E_0\, e^{-jk_0 x\sin\phi} \sum_{n=-\infty}^{\infty} T_n\, e^{j\gamma_n z}\, e^{-j2n\pi x/s} \tag{6}$$

where $k_0 = \omega\sqrt{\mu_0\varepsilon_0}$, $k_0 = 2\pi/\lambda$ is the wave number of free space and λ is wavelength, μ_0 and ε_0 are permeability and permittivity of free space, E_0 is the magnitude of the incident electric field and is set to be 1 in this paper, $k_i = \omega\sqrt{\mu_0\varepsilon_0\varepsilon_{ri}} = k_0\sqrt{\varepsilon_{ri}}$, $i = 2,\ 3,\ 4$, $\beta_n = k_0\sin\phi + 2n\pi/s$, A_n, B_{ni}, C_{ni}, and T_n are unknown coefficients to be determined, and the tangential magnetic field of each region can be obtained by using Maxwell's equation ($\nabla \times \overline{E} = -j\mu\omega\overline{H}$).

Applying the continuity of tangential electromagnetic fields to the boundaries at $z = 0$, t_2, and t_3, we can express C_{n2} in terms of B_{n2} as[9]

$$C_{n2} = p_{n2}\, B_{n2} \tag{7}$$

where

$$p_{n2} = \left[\frac{\exp(-2j\eta_{n3}t_2)(\eta_{n2}-\eta_{n3}) + p_{n1}(\eta_{n2}+\eta_{n3})}{\exp(-2j\eta_{n3}t_2)(\eta_{n2}+\eta_{n3}) + p_{n1}(\eta_{n2}-\eta_{n3})}\right] \exp(-2j\eta_{n2}t_2) \tag{8}$$

$$p_{n1} = \left[\frac{\exp(-2j\eta_{n4}t_3)(\eta_{n3}-\eta_{n4})(\eta_{n4}-\gamma_n) + (\eta_{n3}+\eta_{n4})(\eta_{n4}+\gamma_n)}{\exp(-2j\eta_{n4}t_3)(\eta_{n3}+\eta_{n4})(\eta_{n4}-\gamma_n) + (\eta_{n3}-\eta_{n4})(\eta_{n4}+\gamma_n)}\right] \exp(-2j\eta_{n3}t_3) \tag{9}$$

Since the tangential electric field must be continuous at $z = t_1$, using eq. (7), we can express B_{n2} in terms of A_n as

$$B_{n2} = \frac{e^{jk_0 t_1\cos\phi}\,\delta_n + A_n}{e^{-j\eta_{n2}t_1} + p_{n2}\, e^{j\eta_{n2}t_1}} \tag{10}$$

where δ_n is the Kronecker delta function.

The surface-current density $\overline{J}(x)$ on the strips can be expanded in a series of Jacobi-polynomial $P_p^{(\alpha,\beta)}(\cdot)$ of the order $\alpha=0$ and $\beta=1$ as a kind of orthogonal polynomials[10] with unknown coefficient f_p, $\overline{J}(x)$ can be written as

$$\overline{J}(x)=\hat{a}_y\ e^{-jk_0 x\sin\phi}\sum_{p=0}^{\infty} f_p\, P_p^{(\alpha,\beta)}(x/h),\quad -h\le x\le h. \tag{11}$$

From the tangential magnetic boundary condition, we get

$$k_0\cos\phi\ e^{jk_0t_1\cos\phi}-\sum_{n=-\infty}^{\infty}\{A_n\gamma_n-\eta_{n2}(B_{n2}e^{-j\eta_{n2}t_1}-C_{n2}e^{j\eta_{n2}t_1})\}e^{-j2n\pi x/s},\ -h\le x\le h$$
$$=\omega\mu_0\sum_{p=0}^{\infty} f_p\, P_p^{(\alpha,\beta)}(x/h). \tag{12}$$

Substituting eq. (7) and (10) into eq. (12), multiplying both sides of eq. (17) by $P_q^{(\alpha,\beta)}(x/h)$ and integrating over the region $-s/2\le x\le s/2$, we obtain the unknown coefficient A_n as

$$A_n=-\frac{k_0\eta_0}{s}\sum_{p=0}^{\infty} f_p\left(\frac{G_{pn}}{\gamma_n-p_{n3}}\right)+e^{jk_0t_1\cos\phi}\left(\frac{k_0\cos\phi+p_{n3}}{\gamma_n-p_{n3}}\right)\delta_n \tag{13}$$

where

$$G_{pn}=\int_{-h}^{h} P_p^{(\alpha,\beta)}(x/h)\ e^{j2n\pi/s}\,dx \tag{14}$$

$$p_{n3}=\left[\frac{\eta_{n2}(e^{-j\eta_{n2}t_1}-p_{n2}\,e^{2j\eta_{n2}t_1}-1)}{e^{-j\eta_{n2}t_1}+p_{n2}\,e^{j\eta_{n2}t_1}}\right] \tag{15}$$

and $\eta_0=\sqrt{\mu_0/\varepsilon_0}$ is the intrinsic impedance in the free space.

The resistive boundary condition on the resistive strips is

$$\overline{E^i}+\overline{E^s}=R(x)\,\overline{J}(x),\qquad z=t_1 \tag{16}$$

where $R(x)$ is the tapered resistivity on the resistive strips, its unit is ohms per squares and is suppressed throughout. The tapered resistivity on the resistive strips in this paper assumes to vary linearly from 0 at one edge to finite resistivity at the other edge.

$$R(x)=R_v(1+x/h),\ -h\le x\le h. \tag{17}$$

where R_v is an arbitrary constant. From eq. (1), (2), (16) and (17), we get

$$e^{jk_0t_1\cos\phi}+\sum_{n=-\infty}^{\infty} A_n\,e^{-j2n\pi x/s}=\sum_{p=0}^{\infty} f_p\,R(x)\,P_p^{(\alpha,\beta)}(x/h),\ -h\le x\le h. \tag{18}$$

Multiplying both sides of eq. (18) by $P_q^{(\alpha,\beta)}(x/h)$ and integrating over the region $-h\le x\le h$, we get

$$\sum_{p=0}^{\infty} f_p\,T_{qp}=\sum_{n=-\infty}^{\infty} A_n\ G_{qn}^{*}+H_q,\quad q=0,1,2,\cdots,\infty \tag{19}$$

where

$$G_{qn}^{*}=\int_{-h}^{h} P_q^{(\alpha,\beta)}(x/h)\ e^{-j2\pi nx/s}\,dx \tag{20}$$

$$T_{qp}=\int_{-h}^{h} R(x)\ P_p^{(\alpha,\beta)}(x/h)\ P_q^{(\alpha,\beta)}(x/h)\,dx \tag{21}$$

$$H_q = \int_{-h}^{h} P_q^{(\alpha,\beta)}(x/h)\, e^{jk_0 t\cos\phi}\, dx \qquad (22)$$

where an * denotes the complex conjugation, eq. (21) can be solved by using the closed form[11], but eq. (20) and (22) are solved by using the extended Simpson's rule[10] because these equations don't have the closed form. Let us replace A_n in eq. (19) with that of eq. (13). This yields the following system of simultaneous linear equations.

$$\sum_{p=0}^{M} f_p Z_{qp} = V_q,\ q = 0, 1, 2, \cdots, M \qquad (23)$$

where

$$Z_{qp} = T_{qp} + \frac{k_0\eta_0}{s} \sum_{n=-N}^{N} \left(\frac{G_{pn}}{\gamma_n - p_{n3}} \right) G_{qn}^{*} \qquad (24)$$

$$V_q = -e^{-jk_0 t_1 \cos\phi} \sum_{n=-N}^{N} \left\{ \delta_n \left(\frac{k_0\cos\phi + p_{n3}}{\gamma_n - p_{n3}} \right) \right\} G_{qn}^{*} + H_q. \qquad (25)$$

To obtain numerical results, we truncate the series in eq. (23) and inverse the matrix to solve these equations for the coefficients f_p, and then we obtain the reflection coefficient $\Gamma_n = A_n$ from eq. (13). The transmission coefficient T_n is expressed as[9]

$$T_n = \frac{8\eta_{n4}\, e^{-j\eta_{n2}t_2}\, e^{-j\eta_{n3}t_3}\, (e^{jk_0 t_1\cos\phi}\,\delta_n + A_n)}{(\eta_{n4}-\gamma_n)(e^{-j\eta_{n2}t_1} + p_{n2}\, e^{j\eta_{n2}t_1})\; p_{n4}\, p_{n5}} \qquad (26)$$

where

$$p_{n4} = e^{-j\eta_{n4}t_3}\left(1+\frac{\eta_{n4}}{\eta_{n3}}\right) + e^{j\eta_{n4}t_3}\, 3\left(1-\frac{\eta_{n4}}{\eta_{n3}}\right)\left(\frac{\eta_{n4}+\gamma_n}{\eta_{n4}-\gamma_n}\right) \qquad (27)$$

$$p_{n5} = e^{-j\eta_{n3}t_2}\left(1+\frac{\eta_{n3}}{\eta_{n2}}\right) + e^{j\eta_{n3}t_2}\left(1-\frac{\eta_{n4}}{\eta_{n3}}\right) p_{n1}. \qquad (28)$$

Ⅲ. Numerical Results

We solved numerically by using FGMM the E-polarized scattering problems by a resistive strip grating with the tapered resistivity on 3 dielectric layers, and the purpose of this paper is find out the effects for the relative permittivity and thickness of 3 dielectric layers and the tapered resistivity of resistive strips. The normalized reflected and transmitted powers can be obtained by using eq. (13) and (26), respectively. To confirm the validity of our numerical results, some numerical results are

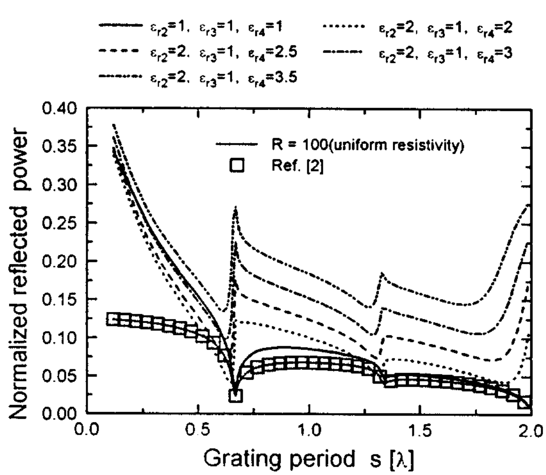

Fig. 2. Geometrically normalized reflected power ($\phi = 30°$, $R_r = 100$, w/s = 0.25, $t_1 = 0.1$, $t_2 = 0.07$, $t_3 = 0.04[\lambda]$).

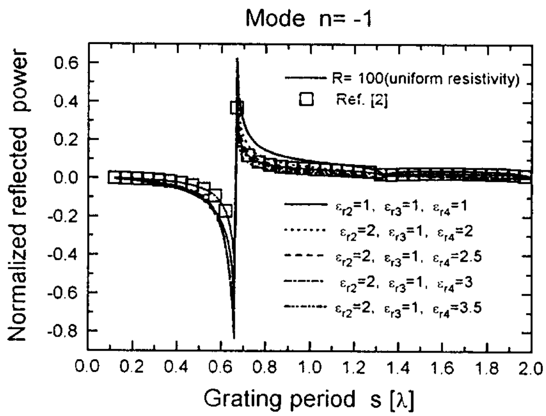

Fig. 3. Normalized reflected power of higher order mode n=-1(ϕ =30°, R_v=100, w/s=0.25, t_1=0.1, t_2=0.07, t_3=0.04[λ]).

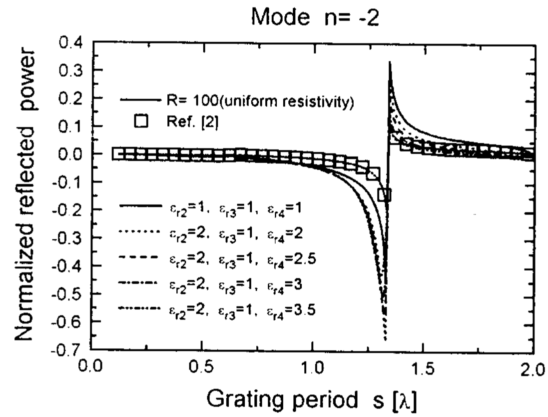

Fig. 5. Normalized reflected power of higher order mode n=-2 (ϕ =30°, R_v=100, w/s=0.25, t_1=0.1, t_2=0.07, t_3=0.04[λ]).

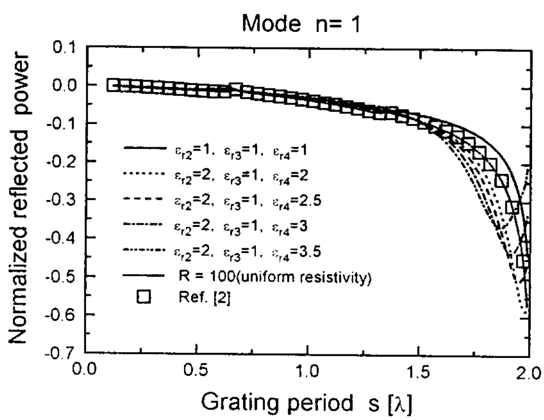

Fig. 4. Normalized reflected power of higher order mode n=1 (ϕ =30°, R_v=100, w/s=0.25, t_1=0.1, t_2=0.07, t_3=0.04[λ]).

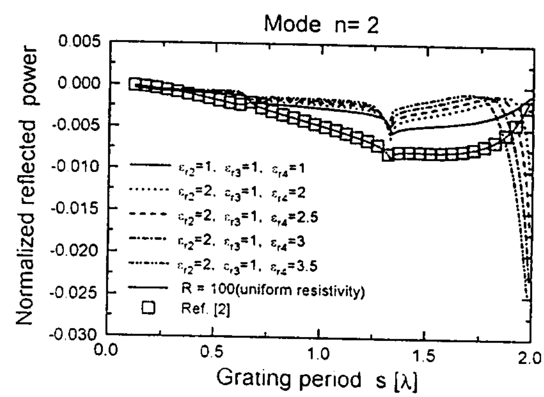

Fig. 6. Normalized reflected power of higher order mode n=2 (ϕ =30°, R_v=100, w/s=0.25, t_1=0.1, t_2=0.07, t_3=0.04[λ]).

compared with those of the existing paper.

Fig. 2 through Fig. 9 show the variation of the normalized reflected and transmitted powers for the relative permittivity of 3 dielectric layers versus the grating period s[λ] for R_v =100 and ϕ =30°, and the numerical results of resistive strip with uniform resistivity ($R(x)$ =100) are also shown for comparision. And the short dots of Fig. 2 through Fig. 9 denote the numerical results of resistive strip with uniform resistivity ($R(x)$=100), and the white squares show the numerical results of the ex-

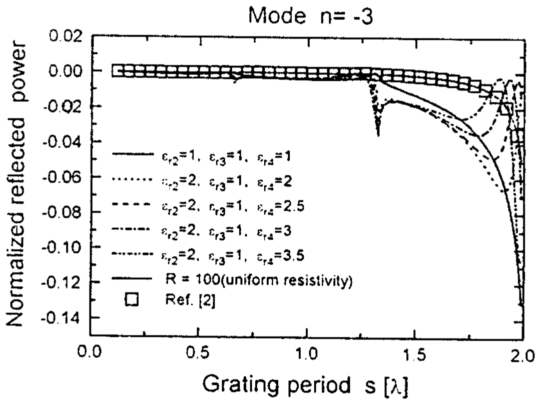

Fig. 7. Normalized reflected power of higher order mode n=−3 (ϕ =30°, $R_{\cdot}$=100, w/s=0.25, t_1=0.1, t_2=0.07, t_3=0.04[λ]).

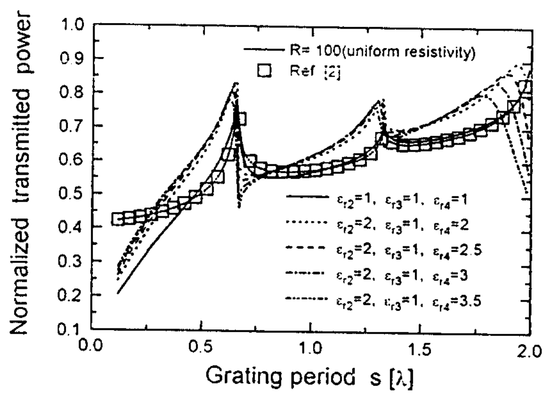

Fig. 9. Geometrically normalized transmitted power (ϕ =30°, $R_{\cdot}$=100, w/s=0.25, t_1=0.1, t_2=0.07, t_3=0.04[λ]).

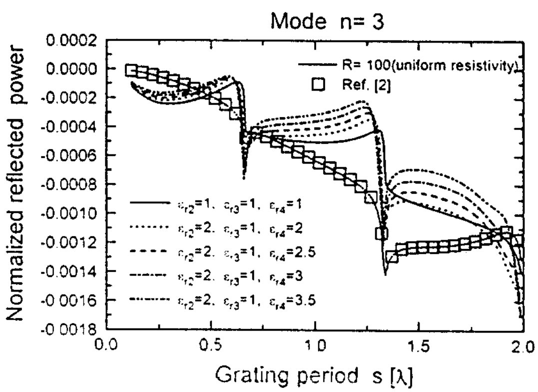

Fig. 8. Normalized reflected power of higher order mode n=3 (ϕ =30°, $R_{\cdot}$=100, w/s=0.25, t_1=0.1, t_2=0.07, t_3=0.04[λ]).

isting paper Ref.[2], so our numerical results are in good agreement with those of the existing paper.

In Fig. 2, it should be noted that the numerical results of resistive strip with tapered resistivity ($R_{\cdot}$=100) are very much different from those of resistive strip with uniform resistivity ($R(x)$=100) below the grating period s=0.66[λ], and the sharp variation points take place at the grating period near s= 0.66[λ] and 1.32[λ]. Fig. 3 through Fig. 8 show the normalized reflected power of the higher order mode n= −1, 1, −2, 2, −3, 3, respectively, and Fig. 9 shows the geometrically normalized transmitted power. To denote propagating and evanescent modes in eq. (3), the values of propagating and evanescent modes are expressed as positive and negative values, respectively. The sharp variation points of the geometrically normalized reflected powers are observed when the reflected power of higher order modes are transferred between propagating and evanescent modes. And in general the local minimum positions of the geometrically normalized reflected power occur at less grating period for the more ε_{r4}.

Fig. 10 and Fig. 11 show the variation of the geometrically normalized reflected and transmitted powers for the relative permittivity of dielectric multilayers versus the incident an-

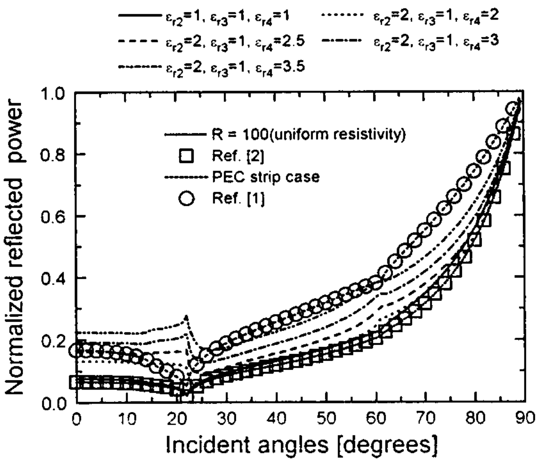

Fig. 10. Geometrically normalized reflected power for angles of incidence (h$=0.3[\lambda]$, s$=6[\lambda]$, $R_v=100$, $t_1=0.1$, $t_2=0.07$, $t_3=0.04[\lambda]$).

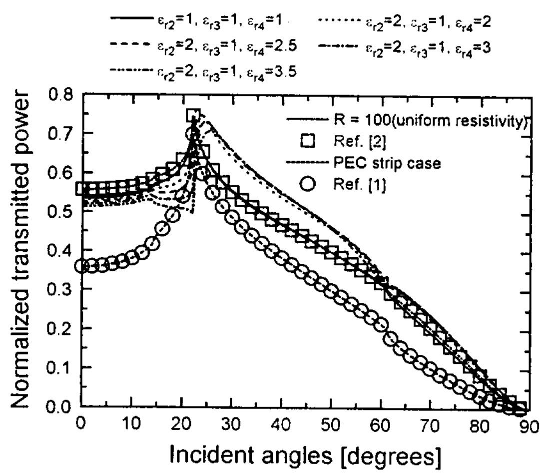

Fig. 11. Geometrically normalized transmitted power for angles of incidence (h$=0.3[\lambda]$, s$=1.6[\lambda]$, $R_v=100$, $t_1=0.1$, $t_2=0.07$, $t_3=0.04[\lambda]$).

gles for $R_v=100$. The white circles denote the numerical results of the existing paper Ref.[1] which treats the problem of the PEC strip case, the short dashes denote the numerical results of the PEC strip case ($R(x)=0$), so our numerical results are in good agreement with those of the existing papers Ref.[1] and Ref.[2].

Finally, the uniform resistivity and PEC strip cases can be obtained by replacing the values of R(x) in eq. (16) with 100 and 0, repectively, so this method can solve the scattering problems for the tapered resistive, uniform resistive, and PEC strip cases.

Ⅳ. Concluding Remarks

In this paper, the E-polarized electromagnetic scattering problems by a resistive strip grating with tapered resistivity on 3 dielectric layers are analyzed to find out the effects for the tapered resistivity of resistive strips and the relative permittivity and thickness on 3 dielectric layers by applying the FGMM. The induced surface current density is expanded in a series of Jacobi-polynomial $P_p^{(\alpha,\beta)}(\cdot)$ of the $\alpha=0$ and $\beta=1$ as a kind of orthogonal polynomials, the tapered resistivity assumes to vary linearly from 0 at one edge to finite resistivity at the other edge. And in general the local minimum positions of the geometrically normalized reflected power occur at less grating period for more relative permittivity of dielectric multilayers. It should be noted that the numerical results of the tapered resistivity are very much different from those of the uniform resistivity and the PEC strip cases. And the sharp variation points of the geometrically normalized reflected power are observed when the reflected power of higher order modes are transferred between propagating and evanescent modes. The proposed method of this paper can solve the scattering problems for the tapered resistive, uniform resistive, and PEC strip cases.

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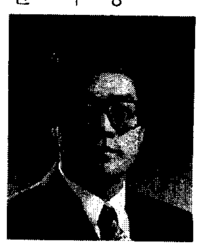
윤 의 중



1958년 7월 7일생

1993년 8월 : 숭실대학교 전자공학과 (공학박사)

1990년 3월~1992년 2월 : 숭실대학교 전자공학과, 한국항공대학교 통신정보공학과 강사

1992년 2월~현재 : 경기전문대학 전자통신과 조교수

1997년~현재 : 대한전자공학회 마이크로파 및 전파전파연구회 간사

[주관심분야] 전자파산란, 수치해석, 초고주파 회로