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Analysis of E-Polaiized Electromagnetic Scattering by a Resistive Strip Grating on Dielectric Multilayers

正會員 尹 義 重*, 梁 承 仁**

多層 誘電體위의 抵抗띠 格子構造에 의한 E-分極 電磁波散亂 解析

Uei-Joong Yoon*, Seung-In Yang** *Regular Members*

ABSTRACT

In this paper, the electromagnetic scattering problem by a resistive strip grating on a dielectric layer of the existing papers is extended to that by a resistive strip grating on dielectric multilayers. The purpose of this paper is to find out the effects for the relative permittivity and thickness of 3 dielectric layers to obtain the geometrically reflected and transmitted powers by using the Fourier-Galerkin moment method. To confirm the validity of the proposed method, the normalized reflected and transmitted powers are obtained by varying the relative permittivity and thickness of dielectric layers are evaluated and compared with those of the existing papers. The numerical results in this paper are in good agreement with those of the existing paper. It should be noticed that 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 according to the increase of the relative permittivity of dielectric layers.

Ⅰ. Introduction

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

*京畿專門大學 電子通信科
**崇實大學校 電子工學科
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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 method (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.

In this paper, the electromagnetic scattering problem by a conducting and resistive strip grating on a dielectric layer of the existing papers [1]-[4] is extended to that by a resistive strip grating on 3 dielectric layers. The problem of multilayers brings more new parameters so that it can get possible to obtain the wanted characteristics. It is solved numerically the E-polarized scattering by a resistive strip grating on 3 dielectric layers by using the FGMM. The purpose of this paper is to find out the effects for the relative permittivity and thickness of 3 dielectric layers. This geometry of problem has been applied extensively to polarizers, frequency filters, the design of radar targets, reflection-type gratings, and many others. And the problem of resistive strip includes the PEC strip case as R = 0, so the resistive strip case of this paper can provide more numerical results than the PEC strip. To explain the sharp variation points, we considered the relation between the geometrically reflected power and the reflected power of the higher order mode.

Ⅱ. Formulation of the Problem

It is considered for the periodic array of thin resistive strip grating on 3 dielectric layers illuminated by a E-polarized plane wave. Fig. 1 shows the cross section of the resistive strip gratings 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, the relative permittivities of the dielectric layers 2, 3, and 4 are ε_{r2}, ε_{r3}, and ε_{r4}, respectively. And w and h denote strip width and a half of strip width(h = w/2).

The incident electric field $\overline{E}^i$ and scattered electric field $\overline{E}^s$ and total electric field $\overline{E}_2^t, \overline{E}_3^t$, $\overline{E}_4^t$, $\overline{E}_5^t$ in the regions 2, 3, 4, and 5 can be written as [9]

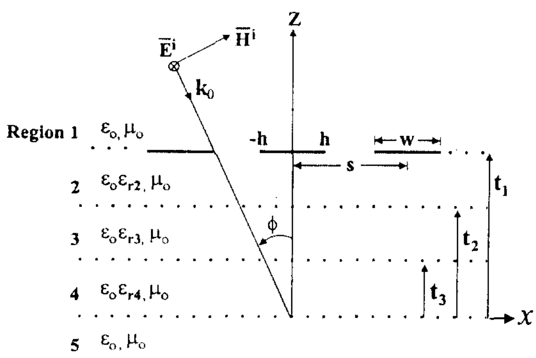

Fig. 1. Geometry of the problem

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

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

$$\gamma_n = \begin{cases} \sqrt{k_0^2 - \beta_n^2}, & k_0^2 \geq \beta_n^2 \\ -j\sqrt{k_n^2 - \beta_0^2}, & k_0^2 \geq \beta_n^2 \end{cases} \tag{3}$$

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

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

$$\overline{E}_5^t = \hat{a}_y E_0 e^{-jk_0 x \sin\phi} \sum_{n=-\infty}^{\infty} T_n e^{j\gamma_n z} e^{-j2n\pi x/s} \tag{6}$$

where $k_0 = \omega\sqrt{\mu_0 \varepsilon_0}$, $k_0 = 2\pi/\lambda$ is wave number of the medium and λ is wavelength, μ_0 and ε_0 are permeability and permittivity in the 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($\nabla \times \overline{E} = -j\mu\omega\overline{E}$).

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

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

$$\exp(-2j\eta_{n3} t_2) \tag{8}$$

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

$$\exp(-2j\eta_{n3} t_3). \tag{9}$$

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.

Let us expand the surface-current density $\overline{J}(x)$ on the strips in a Fourier series with unknown coefficient f_p, $\overline{J}(x)$ can be written as

$$\overline{J}(x) = \hat{a}_y e^{-jk_0 x \sin\phi} \sum_{p=-\infty}^{\infty} f_p e^{jp\pi x/h}, \; -h \le x \le h. \tag{11}$$

From the tangential magnetic boundary condition, we get

$$k_0 \cos\phi e^{jk_0 t_1 \cos\phi} - \sum_{n=-\infty}^{\infty} \{A_n \gamma_n - \eta_{n2}(B_{n2} e^{-j\eta_{n2} t_1} - C_{n2} e^{j\eta_{n2} t_1})\} e^{-j2n\pi x/s}$$

$$= \omega\mu_0 \sum_{p=-\infty}^{\infty} f_p e^{jp\pi x/h}, \; -h \le x \le h. \tag{12}$$

Substituting eq. (7) into eq. (12) Substituting eq. (7) into eq. (12), multiplying both sides of eq. (12) by $e^{j2n\pi x/s}$ and integrating over the region $-s/2 \le x \le s/2$, we obtain the unknown coefficient A_n as

$$A_n = -\frac{k_0 \eta_0}{s} \sum_{p=-\infty}^{\infty} f_p \left(\frac{G_{pn}}{\gamma_n - p_{n3}} \right)$$

$$+ e^{jk_0 t_1 \cos\phi} \left(\frac{k_0 \cos\phi + p_{n3}}{\gamma_n - p_{n3}} \right) \delta_n \tag{13}$$

where

$$G_{pn} = \int_{-h}^{h} e^{j2\pi(p/w + n/s)} dx \tag{14}$$

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

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

The resistive boundary condition is

$$\overline{E}^i + \overline{E}^s = R \overline{J}(x), \text{ on the resistive strips} \tag{16}$$

where R is the uniform resistivity of the strips, its unit is ohms per square and suppressed below. From eq. (1), (2), (11), and (16), we get

$$e^{jk_0 t_1 \cos\phi} + \sum_{n=-\infty}^{\infty} A_n e^{-j2n\pi x/s} = R \sum_{p=-\infty}^{\infty} f_p e^{jp\pi x/h}. \tag{17}$$

We multiply both sides of eq. (17) by $e^{-j q\pi x/h}$ and integrate over the region $-h \le x \le h$ to obtain

$$\sum_{n=-\infty}^{\infty} A_n G_{qn}^* = R\mathrm{w} \sum_{p=-\infty}^{\infty} f_p \delta_{qp} - \mathrm{w}\, \delta_q e^{jk_0 t_1 \cos\phi} \tag{18}$$

where $*$ denotes the complex conjugate, δ_{qp} is the diagonal square matrix. Let us replace A_n in eq. (18) with that of eq. (13). This yields the following system of simultaneous linear equations.

$$\sum_{p=-M}^{M} f_p Z_{qp} = V_q, \; q = 0, 1, 2, \cdots, M \tag{19}$$

where

$$Z_{qp} = R\mathrm{w}\, \delta_{qp} + \frac{k_0 \eta_0}{s} \sum_{n=-N}^{N} \left(\frac{G_{qn}^*}{\gamma_n - p_{n3}} \right) G_{pn} \tag{20}$$

$$V_q = e^{jk_0 t_1 \cos\phi} \left[\mathrm{w}\, \delta_q + \sum_{n=-N}^{N} \delta_n \left(\frac{k_0 \cos\phi + p_{n3}}{\gamma_n - p_{n3}} \right) G_{qn}^* \right]. \tag{21}$$

To obtain numerical results, we inverse eq. (19) for unknown 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]

$$T_n=\frac{8\eta_{n4}\, e^{-j\eta_{n2}t_2}\, e^{-j\eta_{n3}t_3}\,(e^{jk_0t_1\cos\phi}\,\delta_n+A_n)}{(\eta_{n4}-\gamma_n)(e^{-j\eta_{n1}t_1}+p_{n2}\, e^{j\eta_{n1}t_1})\, p_{n4}\, p_{n5}} \tag{22}$$

where

$$p_{n4}=e^{-j\eta_{n4}t_3}\left(1+\frac{\eta_{n4}}{\eta_{n3}}\right)+e^{j\eta_{n4}t_3}\left(1-\frac{\eta_{n4}}{\eta_{n3}}\right)\left(\frac{\eta_{n4}+\gamma_n}{\eta_{n4}-\gamma_n}\right) \tag{23}$$

$$p_{n5}=e^{-j\eta_{n3}t_2}\left(1+\frac{\eta_{n3}}{\eta_{n2}}\right)+e^{j\eta_{n3}t_2}\left(1+\frac{\eta_{n4}}{\eta_{n3}}\right)p_{n1}. \tag{24}$$

Ⅲ. Numerical Results

In this paper, The E-polarized scattering problem is numerically calculated the normalized reflected and transmitted powers on 3 dielectric layers by using the FGMM. The normalized reflected and transmitted powers are obtained by varying the relative permittivity and thickness of 3 dielectric layers. And the normalized reflected and transmitted powers can be obtained by using eqs. (13) and (22), respectively. To confirm the validity of our numerical results, some numerical results are compared with those of the existing papers [1, 2].

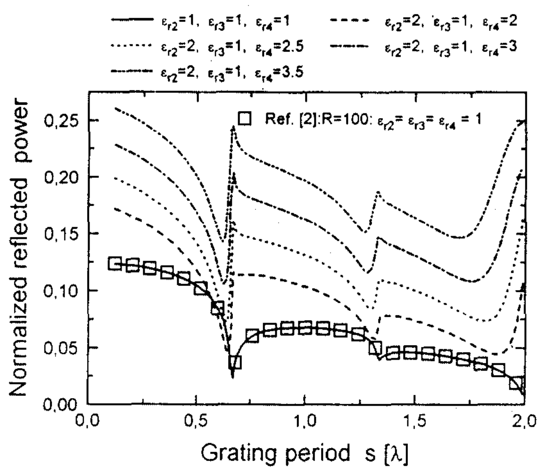

Fig. 2. Geometrically normalized reflected power ($\phi=30^o$, w/s = 0.25, $t_1=0.1$, $t_2=0.07$, $t_3=0.04$[λ], $R=100$)

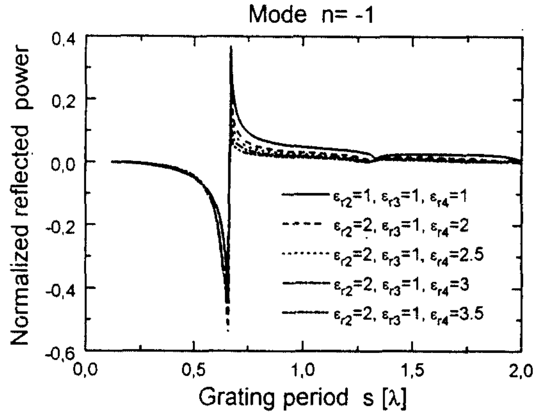

Fig. 3. Normalized reflected power of higher order mode n = −1 ($\phi=30^o$, w/s = 25, $t_1=0.1$, $t_2=0.07$, $t_3=0.04$[λ], $R=100$)

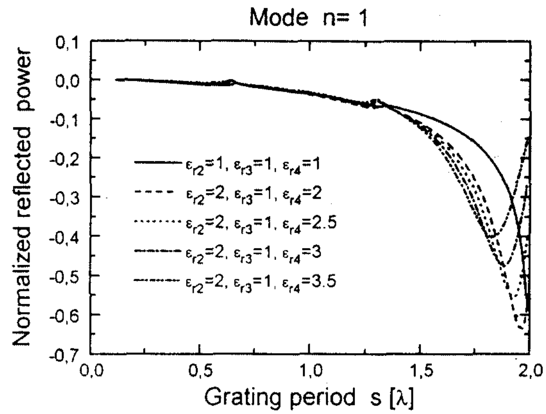

Fig. 4. Normalized reflected power of higher order mode n = 1 ($\phi=30^o$, w/s = 0.25, $t_1=0.1$, $t_2=0.07$, $t_3=0.04$[λ], $R=100$)

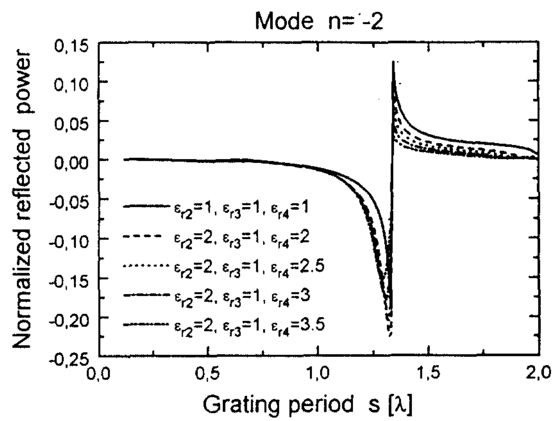

Fig. 5. Normalized reflected power of higher order mode n = −2 ($\phi=30^o$, w/s = 0.25, $t_1=0.1$, $t_2=0.07$, $t_3=0.04$[λ], $R=100$)

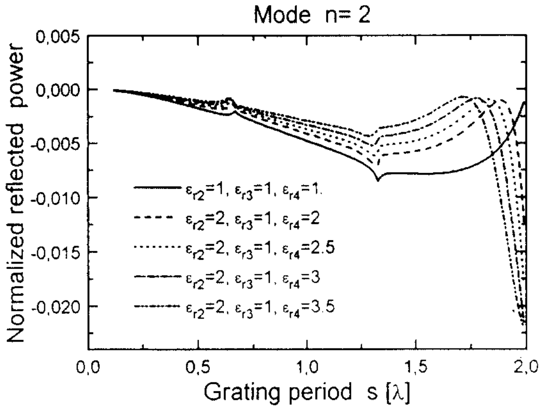

Fig. 6. Normalized reflected power of higher order mode n = 2 ($\phi = 30^o$, w/s = 0.25, $t_1 = 0.1$, $t_2 = 0.07$, $t_3 = 0.04[\lambda]$, $R = 100$)

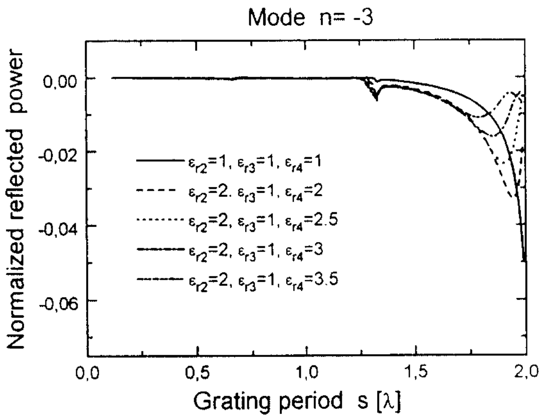

Fig. 7. Normalized reflected power of higher order mode n = −3 ($\phi = 30^o$, w/s = 0.25, $t_1 = 0.1$, $t_2 = 0.07$, $t_3 = 0.04[\lambda]$, $R = 100$)

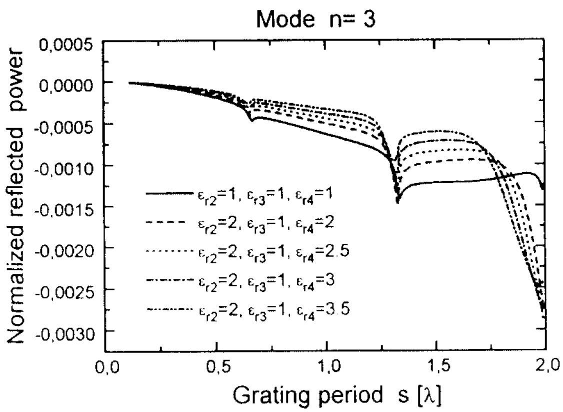

Fig. 8. Normalized reflected power of higher order mode n = 3 ($\phi = 30^o$, w/s = 0.25, $t_1 = 0.1$, $t_2 = 0.07$, $t_3 = 0.04[\lambda]$, $R = 100$)

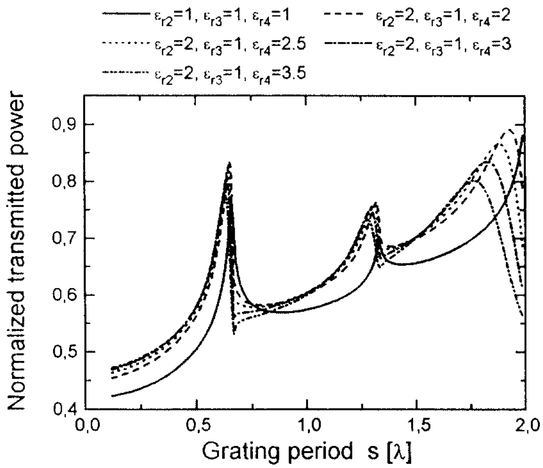

Fig. 9. Geometrically normalized transmitted power ($\phi = 30^o$, w/s = 0.25, $t_1 = 0.1$, $t_2 = 0.07$, $t_3 = 0.04[\lambda]$, $R = 100$)

Fig. 2 through Fig. 9 show the variation of the normalized reflected and transmitted powers for the relative permittivity of the dielectric multilayers versus the grating period s[λ] for the uniform resistivity R = 100 [Ω/square] and incident angle $\phi = 30^o$. Fig. 3 through Fig. 8 show the normalized reflected power of the higher order mode n = −1, 1, −2, 2, −3, 3, respectively. The sharp variation points of Fig. 2 take place at the grating periods near s = 0.66[λ] and 1.32 [λ], respectively. To denote propagating and evanescent modes in eq. (3), the values of propagating and evanescent modes are expressed as positive and negative values, respectively. It should be noticed that the sharp variation points of the geometrically normalized reflected and transmitted powers are observed when the higher order modes n = −1 and −2 cases shown in Fig. 3 and 5 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 according to the increase of the value of ε_{r4}.

Fig. 10 and Fig. 11 show the variation of the geometrically normalized reflected and transmitted

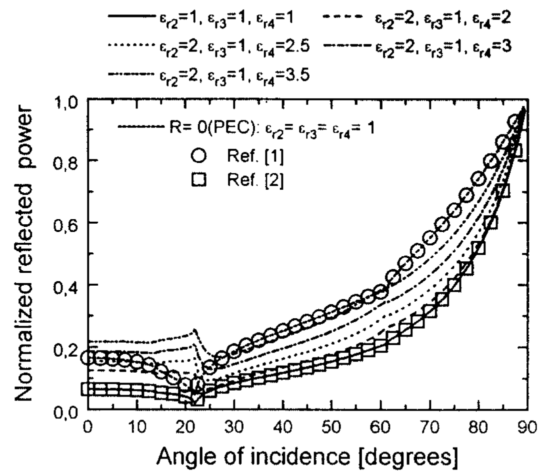

Fig. 10. Geometrically normalized reflected power for angles of incidence
(h = 0.3[λ], s = 1.6[λ], t_1 = 0.1, t_2 = 0.07, t_3 = 0.04[λ], R = 100)

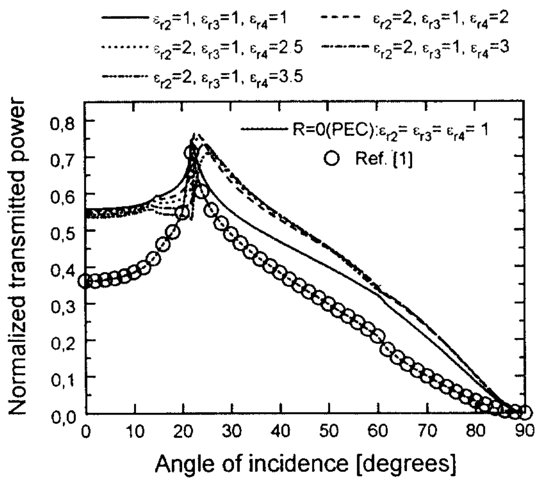

Fig. 11. Geometrically normalized transmitted power for angles of incidence
(h = 0.3[λ], s = 1.6[λ], t_1 = 0.1, t_2 = 0.07, t_3 = 0.04[λ], R = 100)

powers for the relative permittivity of dielectric multilayers versus the incident angles for the R = 0 [Ω/square] which is the PEC strip case and the uniform resistivity R = 100[Ω/square]. The white circle and squares denote the numerical results of the existing papers Ref. [1] and [2] which treat the problem of the PEC strip and uniform resistive strip, respectively. These are exactly the same cases as our multilayers case for $\varepsilon_{r2} = \varepsilon_{r3} = \varepsilon_{r4} = 1$. Therefore our numerical results are in good agreement with those of the existing papers.

Ⅳ. Concluding Remark

In this paper, the electromagnetic scattering problem by a resistive strip grating on a dielectric layer of the existing papers is extended to that by a resistive strip grating on dielectric multilayers. The E-polarized electromagnetic scattering problem by a resistive strip grating on 3 dielectric layers is numerically calculated by using the FGMM. The purpose of this paper is to find out the effects for the relative permittivity and thickness of 3 electric layers. To confirm the validity of the proposed method, our numerical results of the normalized reflected and transmitted powers are compared with those of the existing paper, then our numerical results are in good agreement with those of the existing paper. The pattern of reflected power in geometry of this paper can be obtained by adjusting the uniform resistivity of resistive strips as well as the relative permittivity and thickness of the dielectric layers. It should be noticed that in general the local minimum positions occur at grating period according to the increase of relative permittivity of the region 4. And the sharp variation points of the geometrically normalized reflected power are observed, this is called Wood's anomaly, when the higher order modes are transferred between propagating and evanescent modes. Therefore it is expected that these results could be applied to the design of reflection-type gratings, frequency filters, and so on.

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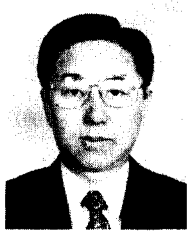
윤 의 중(Uei-Joong Yoon) 정회원

1988년 3월 : 숭실대학교 전자공학과 대학원 박사과정 입학
1990년 3월~1992년 2월 : 숭실대학교 전자공학과 및 한국항공대학교 항공정보통신공학과 강사
1993년 8월 : 숭실대학교 전자공학과(공학박사)
1992년 2월~현재 : 경기전문대학 전자통신과 조교수
1997년~현재 : 대한전자공학회 마이크로파 및 전파전파연구회 간사
※주관심분야 : 전자파산란, 수치해석, 초고주파회로



양 승 인(Seung-In Yang) 정회원

1974년 2월 : 서울대학교 전기공학과(공학사)
1976년 2월 : 한국과학기술원 전기 및 전자공학과(공학석사)
1987년 8월 : 한국과학기술원 전기 및 전자공학과(공학박사)
1983년~1984년 : University of Michigan, Radiation Lab.(객원연구원)
1991년~1992년 : University of Colorado, MIMICAD Center(객원교수)
1990년~현재 : 한국통신기술협회 RSG-9 의장
1996년~1997년 : 한국전자파학회 학술이사
1997년~현재 : 대한전자공학회 마이크로파 및 전파전파연구회 전문위원장
1978년~현재 : 숭실대학교 전자공학과 교수
※주관심분야 : 전자파산란, 수치해석, 안테나, 초고주파회로