Backscattering of TE Waves by Periodical Surface with Dielectric Cover

Jean-Fu Kiang, *Member, IEEE*

***Abstract*— Several types of periodical surfaces are studied on their backscattering to a normally incident TE plane wave. The surfaces are perfect conductor and are covered with dielectric materials to make a flat surface due to aerodynamic consideration. The effects of frequency, surface profile shape, period-to-depth ratio, and cover permittivity are analyzed. It is observed that a sawtooth profile can be used to reduce the backscattering at high frequencies and elliptical profiles can be used to reduce the backscattering at certain low frequencies when a cover material is filled in the grooves.**

***Index Terms*—Electromagnetic scattering, periodic structures.**

I. Introduction

PERIODICAL structures have been widely studied for applications such as filters and leaky wave antennas [1], wave transmission and reflection [2], scattering [3], diffraction by a Fourier grating [4], scattering from conductive surfaces with a sinusoidal height profile [5], [6], reflection and transmission by conductive or dielectric gratings embedded in a dielectric slab [7], etc.

When a plane wave is incident upon a periodical surface, higher order (Floquet) modes other than the specularly reflected mode are scattered in directions determined by the periodical boundary conditions. The higher order modes carry away part of the incident power, hence, reduce the specularly reflected power. In [5] and [6], it is observed that the profile depth of the surface affects the ratio between the specularly reflected power and the power carried by the first-order Floquet modes. This property can be used to reduce the radar cross section of moving objects of which the grooves need be filled by dielectric materials to have an aerodynamically smooth surface. Thus, the effects of the dielectric cover on the backscattering cross section need to be considered.

In this paper, we develop a mode-matching method by which periodical surfaces of arbitrary profiles filled with layered dielectric can be analyzed. The mode-matching method is formulated in the next section, followed by the numerical results with the sinusoidal, sawtooth, convex elliptical, and concave elliptical surface profiles.

Manuscript received November 19, 1996; revised July 9, 1997. This work was supported by the National Science Council, Taiwan, under Contract NSC86-2221-E005-021, the Chunghwa Telecommunications Laboratory, Taiwan, under Contract NSC86-2209, and the Chung-Shan Institute of Science and Technology, Taiwan, under Contract CS86-0210-D005-001.

The author is with the Department of Electrical Engineering, National Chung-Hsing University, Taichung, Taiwan, 402 ROC.

Publisher Item Identifier S 0018-926X(98)01485-9.

II. Formulation

Fig. 1 shows a TE plane wave incident upon a perfectly conducting surface which is uniform in the y direction and is periodical in the x direction with the period of P. The periodical surface is modeled as a cascaded step function and the medium in the groove below $z=0$ is modeled as a layered medium. The ℓth layer starts at $x=x_\ell$, its width is a_ℓ, and it contains a medium of permittivity ϵ_ℓ. The fields in layer (0) can be represented as a superposition of Floquet modes [8]

$$\begin{aligned}\bar{E}_0 &= \hat{y}E_o\left\{e^{ik_x x - ik_z z} + \sum_{n=-\infty}^{\infty}\tilde{R}_n e^{ik_{xn}x + ik_{0zn}z}\right\}\\ \bar{H}_0 &= \hat{x}E_o\left\{\frac{k_z}{\omega\mu_o}e^{ik_x x - ik_z z} - \sum_{n=-\infty}^{\infty}\tilde{R}_n\frac{k_{0zn}}{\omega\mu_o}e^{ik_{xn}x+ik_{0zn}z}\right\}\\ &\quad + \hat{z}E_o\left\{\frac{k_x}{\omega\mu_o}e^{ik_x x - ik_z z} + \sum_{n=-\infty}^{\infty}\tilde{R}_n\frac{k_{xn}}{\omega\mu_o}e^{ik_{xn}x+ik_{0zn}z}\right\}\end{aligned} \tag{1}$$

where $k_x = k_o\sin\theta$ and $k_z = k_o\cos\theta$ are the wave vector components of the incident plane wave, $k_{xn} = k_x + 2n\pi/P$ is the x component of the wave vector of the nth Floquet mode, $k_{0zn} = \sqrt{k_o^2 - k_{xn}^2}$ with $\mathrm{Im}(k_{0zn}) \geq 0$, and $\tilde{R}_n$ is the amplitude of the nth reflected Floquet mode when the incident wave has a unity amplitude. The fields in layer (ℓ) of the groove can be expanded in terms of the parallel plate waveguide modes as [9]

$$\begin{aligned}\bar{E}_\ell &= \hat{y}E_o\sum_{m=1}^{\infty}\sin[\gamma_{\ell m}(x-x_\ell)]\big[\alpha_{\ell m}e^{ik_{\ell zm}z_\ell}\\ &\quad + \beta_{\ell m}e^{-ik_{\ell zm}z_\ell}\big], \quad 1\leq\ell\leq N\\ \bar{H}_\ell &= -\hat{x}E_o\sum_{m=1}^{\infty}\sin[\gamma_{\ell m}(x-x_\ell)]\left(\frac{k_{\ell zm}}{\omega\mu_\ell}\right)\big[\alpha_{\ell m}e^{ik_{\ell zm}z_\ell}\\ &\quad - \beta_{\ell m}e^{-ik_{\ell zm}z_\ell}\big] + \hat{z}E_o\sum_{m=1}^{\infty}\cos[\gamma_{\ell m}(x-x_\ell)]\left(\frac{\gamma_{\ell m}}{i\omega\mu_\ell}\right)\\ &\quad \times\big[\alpha_{\ell m}e^{ik_{\ell zm}z_\ell} + \beta_{\ell m}e^{-ik_{\ell zm}z_\ell}\big], \quad 1\leq\ell\leq N\end{aligned} \tag{2}$$

where $z_\ell = z + d_\ell$, $\gamma_{\ell m} = m\pi/a_\ell$, and $k_{\ell zm} = \sqrt{\omega^2\mu_\ell\epsilon_\ell - \gamma_{\ell m}^2}$ with $\mathrm{Im}(k_{\ell zm}) \geq 0$. To obtain a more compact representation, define coefficient vectors $\bar{\alpha}_\ell = [\alpha_{\ell 1}, \alpha_{\ell 2}, \cdots]^t$, $\bar{\beta}_\ell = [\beta_{\ell 1}, \beta_{\ell 2}, \cdots]^t$, and diagonal matrices $\bar{\bar{K}}_\ell = \mathrm{diag}\{k_{\ell z1}, k_{\ell z2}, \cdots\}$. At $z = -d_\ell$, define a reflection matrix $\bar{\bar{R}}_{\cap\ell}$ such that $\bar{\alpha}_\ell = \bar{\bar{R}}_{\cap\ell}\cdot\bar{\beta}_\ell$, which means that the amplitudes of the downward-propagating wave modes multiplied by the downward reflection matrix give the

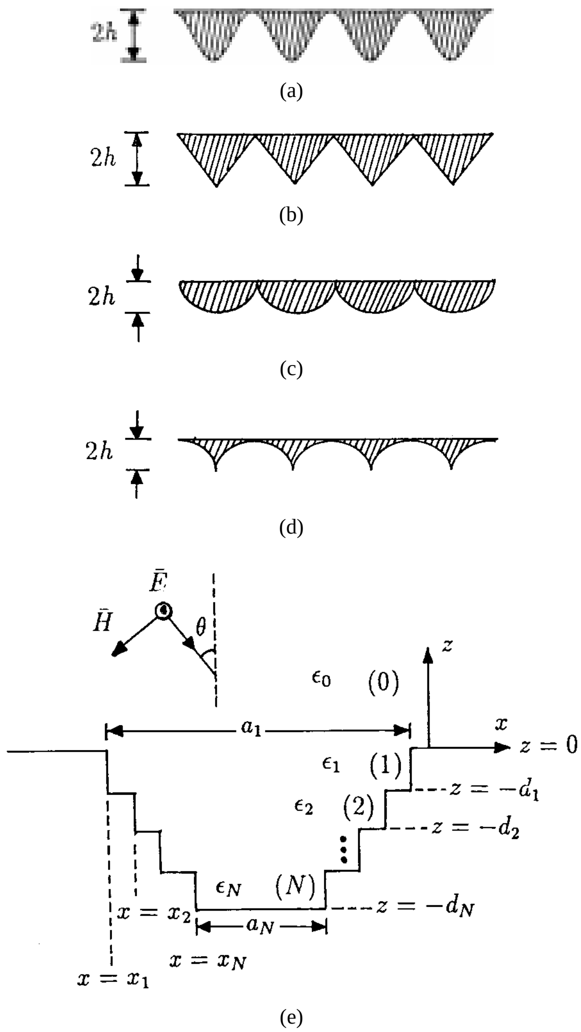

Fig. 1. Periodical surface profiles. (a) Sinusoidal profile. (b) Sawtooth profile. (c) Concave elliptical profile. (d) Convex elliptical profile. (Hatching represents dielectric cover.) (e) Cascaded layers model of the periodical surface.

amplitudes of the upward wave modes. An upward reflection matrix can be defined at $z = -d_{\ell-1}$ in a similar way as $e^{-i\bar{\bar{K}}_\ell h_\ell} \cdot \bar{\beta}_\ell = \bar{\bar{R}}_{\cup\ell} \cdot e^{i\bar{\bar{K}}_\ell h_\ell} \cdot \bar{\alpha}_\ell$ where $h_\ell = d_\ell - d_{\ell-1}$.

The continuity of tangential electric fields at $z = -d_\ell$ implies

$$E_{\ell y} = \begin{cases} E_{(\ell+1)y}, & 0 \le x - x_{\ell+1} \le a_{\ell+1} \\ 0, & \text{elsewhere.} \end{cases} \tag{3}$$

Substitute the field expressions in (2) into (3), multiply the resulting equation by $(2/a_\ell)\sin[\gamma_{\ell n}(x - x_\ell)]$, then integrate over $x_\ell \le x \le x_\ell + a_\ell$ to obtain

$$(\bar{\bar{R}}_{\cap\ell} + \bar{\bar{I}}) \cdot \bar{\beta}_\ell = \bar{\bar{C}}^{\ell(\ell+1)} \cdot \left(e^{i\bar{\bar{K}}_{\ell+1}h_{\ell+1}} \cdot \bar{\bar{R}}_{\cap(\ell+1)} \cdot e^{i\bar{\bar{K}}_{\ell+1}h_{\ell+1}} + \bar{\bar{I}}\right) \cdot e^{-i\bar{\bar{K}}_{\ell+1}h_{\ell+1}} \cdot \bar{\beta}_{\ell+1} \tag{4}$$

where the (n,m)th element of $\bar{\bar{C}}^{\ell(\ell+1)}$ is

$$C_{nm}^{\ell(\ell+1)} = \frac{2}{a_\ell}\int_{x_{\ell+1}}^{x_{\ell+1}+a_{\ell+1}} dx \sin[\gamma_{\ell n}(x - x_\ell)] \times \sin[\gamma_{(\ell+1)m}(x - x_{\ell+1})]. \tag{5}$$

The continuity of tangential magnetic fields at $z = -d_\ell$ implies

$$H_{\ell x} = H_{(\ell+1)x}, \qquad 0 \le x - x_{\ell+1} \le a_{\ell+1} \tag{6}$$

Substitute the field expressions in (2) into (6), multiply the resulting equation by $(2/a_{\ell+1})\sin[\gamma_{(\ell+1)n}(x - x_{\ell+1})]$, then integrate over $x_{\ell+1} \le x \le x_{\ell+1} + a_{\ell+1}$ to obtain

$$\bar{\bar{D}}^{(\ell+1)\ell} \cdot \frac{\bar{\bar{K}}_\ell}{\omega\mu_\ell} \cdot \left(\bar{\bar{R}}_{\cap\ell} - \bar{\bar{I}}\right) \cdot \bar{\beta}_\ell = \frac{\bar{\bar{K}}_{\ell+1}}{\omega\mu_{\ell+1}} \cdot \left(e^{i\bar{\bar{K}}_{\ell+1}h_{\ell+1}} \cdot \bar{\bar{R}}_{\cap(\ell+1)} \cdot e^{i\bar{\bar{K}}_{\ell+1}h_{\ell+1}} - \bar{\bar{I}}\right) \cdot e^{-i\bar{\bar{K}}_{\ell+1}h_{\ell+1}} \cdot \bar{\beta}_{\ell+1} \tag{7}$$

where the (n,m)th element of $\bar{\bar{D}}^{(\ell+1)\ell}$ is

$$D_{nm}^{(\ell+1)\ell} = \frac{2}{a_{\ell+1}}\int_{x_{\ell+1}}^{x_{\ell+1}+a_{\ell+1}} dx \sin[\gamma_{(\ell+1)n}(x - x_{\ell+1})] \times \sin[\gamma_{\ell m}(x - x_\ell)]. \tag{8}$$

From (4) and (7), a recursive formula of the reflection matrices is obtained

$$\begin{aligned} \bar{\bar{R}}_{\cap\ell} = \Bigg\{ & \bar{\bar{C}}^{\ell(\ell+1)} \cdot \left(e^{i\bar{\bar{K}}_{\ell+1}h_{\ell+1}} \cdot \bar{\bar{R}}_{\cap(\ell+1)} \cdot e^{i\bar{\bar{K}}_{\ell+1}h_{\ell+1}} + \bar{\bar{I}}\right) \\ & \cdot \left(e^{i\bar{\bar{K}}_{\ell+1}h_{\ell+1}} \cdot \bar{\bar{R}}_{\cap(\ell+1)} \cdot e^{i\bar{\bar{K}}_{\ell+1}h_{\ell+1}} - \bar{\bar{I}}\right)^{-1} \\ & \cdot \frac{\mu_{\ell+1}}{\mu_\ell}\bar{\bar{K}}_{\ell+1}^{-1} \cdot \bar{\bar{D}}^{(\ell+1)\ell} \cdot \bar{\bar{K}}_\ell - \bar{\bar{I}} \Bigg\}^{-1} \\ & \cdot \Bigg\{ \bar{\bar{C}}^{\ell(\ell+1)} \cdot \left(e^{i\bar{\bar{K}}_{\ell+1}h_{\ell+1}} \cdot \bar{\bar{R}}_{\cap(\ell+1)} \cdot e^{i\bar{\bar{K}}_{\ell+1}h_{\ell+1}} + \bar{\bar{I}}\right) \\ & \cdot \left(e^{i\bar{\bar{K}}_{\ell+1}h_{\ell+1}} \cdot \bar{\bar{R}}_{\cap(\ell+1)} \cdot e^{i\bar{\bar{K}}_{\ell+1}h_{\ell+1}} - \bar{\bar{I}}\right)^{-1} \\ & \cdot \frac{\mu_{\ell+1}}{\mu_\ell}\bar{\bar{K}}_{\ell+1}^{-1} \cdot \bar{\bar{D}}^{(\ell+1)\ell} \cdot \bar{\bar{K}}_\ell + \bar{\bar{I}} \Bigg\}. \end{aligned} \tag{9}$$

Since the tangential electric field at $z = -d_N$ vanishes, we have $\bar{\bar{R}}_{\cap N} = -\bar{\bar{I}}$. The reflection matrices at $z = -d_{N-1}, \cdots, z = -d_1, z = 0$ can be obtained from (9) starting from $\bar{\bar{R}}_N$.

The continuity of tangential electric fields at $z = 0$ implies

$$E_{0y} = \begin{cases} E_{1y}, & 0 \le x - x_1 \le a_1 \\ 0, & \text{elsewhere.} \end{cases} \tag{10}$$

Substitute the field expressions in (1) and (2) into (10), multiply the resulting equation by $(1/P)e^{-ik_{xn}x}$, then integrate over $0 \le x \le P$ to obtain

$$\bar{R} + \bar{I}_1 = \bar{\bar{T}} \cdot \left(e^{i\bar{\bar{K}}_1 h_1} \cdot \bar{\bar{R}}_{\cap 1} \cdot e^{i\bar{\bar{K}}_1 h_1} + \bar{\bar{I}}\right) \cdot e^{-i\bar{\bar{K}}_1 h_1} \cdot \bar{\beta}_1 \tag{11}$$

where $\bar{R} = [\cdots, R_{-1}, R_0, R_1, \cdots]^t$ is the vector consisting of all the reflection coefficients $\{R_n\}$, $\bar{I}_1 = [\cdots, 0, 1, 0, \cdots]^t$ is the incident wave vector in which the only nonzero element corresponds to the incident wave and the (n,m)th element of $\bar{\bar{T}}$ is

$$T_{nm} = \frac{1}{P}\int_{x_1}^{x_1+a_1} dx e^{-ik_{xn}x} \sin[\gamma_{1m}(x - x_1)]. \tag{12}$$

The continuity of tangential magnetic fields at $z = 0$ implies

$$H_{0x} = H_{1x}, \quad 0 \le x - x_1 \le a_1. \tag{13}$$

Substitute the field expressions in (1) and (2) into (13), multiply the resulting equation by $(2/a_1)\sin[\gamma_{1n}(x-x_1)]$, then integrate over $x_1 \leq x \leq x_1 + a_1$ to obtain

$$\bar{\bar{S}} \cdot \frac{\bar{\bar{K}}_0}{\omega\mu_0} \cdot (\bar{R} - \bar{I}_1) = \frac{\bar{\bar{K}}_1}{\omega\mu_1} \cdot \left(e^{i\bar{\bar{K}}_1 h_1} \cdot \bar{\bar{R}}_{\cap 1} \cdot e^{i\bar{\bar{K}}_1 h_1} - \bar{\bar{I}}\right) \cdot e^{-i\bar{\bar{K}}_1 h_1} \cdot \bar{\beta}_1 \quad (14)$$

where the (n, m)th element of $\bar{\bar{S}}$ is

$$S_{nm} = \frac{2}{a_1} \int_{x_1}^{x_1+a_1} dx \sin[\gamma_{1n}(x - x_1)] e^{ik_{xm}x}. \quad (15)$$

From (11) and (14), we have

$$\begin{aligned}\bar{R} = &\Big\{\bar{\bar{T}} \cdot \left(e^{i\bar{\bar{K}}_1 h_1} \cdot \bar{\bar{R}}_{\cap 1} \cdot e^{i\bar{\bar{K}}_1 h_1} + \bar{\bar{I}}\right) \\ &\cdot \left(e^{i\bar{\bar{K}}_1 h_1} \cdot \bar{\bar{R}}_{\cap 1} \cdot e^{i\bar{\bar{K}}_1 h_1} - \bar{\bar{I}}\right)^{-1} \cdot \frac{\mu_1}{\mu_o} \bar{\bar{K}}_1^{-1} \\ &\cdot \bar{\bar{S}} \cdot \bar{\bar{K}}_0 - \bar{\bar{I}}\Big\}^{-1} \\ &\cdot \Big\{\bar{\bar{T}} \cdot \left(e^{i\bar{\bar{K}}_1 h_1} \cdot \bar{\bar{R}}_{\cap 1} \cdot e^{i\bar{\bar{K}}_1 h_1} + \bar{\bar{I}}\right) \\ &\cdot \left(e^{i\bar{\bar{K}}_1 h_1} \cdot \bar{\bar{R}}_{\cap 1} \cdot e^{i\bar{\bar{K}}_1 h_1} - \bar{\bar{I}}\right)^{-1} \cdot \frac{\mu_1}{\mu_o} \bar{\bar{K}}_1^{-1} \\ &\cdot \bar{\bar{S}} \cdot \bar{\bar{K}}_0 + \bar{\bar{I}}\Big\} \cdot \bar{I}_1. \end{aligned} \quad (16)$$

The refelection coefficients of all the Floquet modes are obtained by solving (16).

III. Results and Discussions

When a plane wave is normally incident upon a periodical surface, the backscattering direction is the same as that of the specular reflection. At oblique incidence, backscattering occurs only when the incident direction is opposite to that of a certain Floquet mode. For moving objects with periodical surfaces, the oblique incidence is of less concern because it rarely happens.

In Fig. 2, we show the reflection coefficient of the zeroth order mode at normal incidence to a periodical surface with sinusoidal profile. The results from [5] without cover material match reasonably well with ours at $h = 0.25\lambda_o$. It is observed that as h either increases or decreases from $0.25\lambda_o$, the reflected power increases compared with that of $h = 0.25\lambda_o$. The reflected power curve has more oscillations with frequency as the profile height h is increased from $0.125\lambda_o$ to $0.5\lambda_o$ because reflections from different portions of a deeper groove experience larger phase difference variation as frequency changes.

In Fig. 3, we show the effects of cover permittivity on the reflected power. As the cover permittivity increases, the wavelength in the cover is scaled by the squared root of the relative permittivity. As ferquency is increased such that $|2n\pi/P|$ becomes less than k_f (the wavenumber of the cover material), the $\pm n$th Floquet modes are excited as propagating modes in the cover. At the air–dielectric interface, these propagating Floquet modes except the zeroth order one are

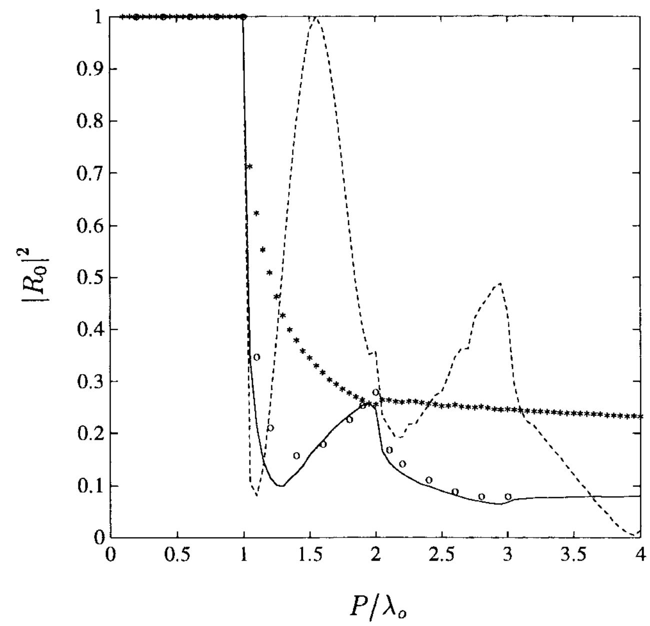

Fig. 2. Magnitude-squared of R_0 with a sinusoidal profile $y = -h + h\cos(2\pi x/P)$, $\epsilon_f = \epsilon_o$, ——: $h = 0.25\lambda_o$, - - -: $h = 0.5\lambda_o$, * * *: $h = 0.125\lambda_o$, o: [6] with $h = 0.25\lambda_o$.

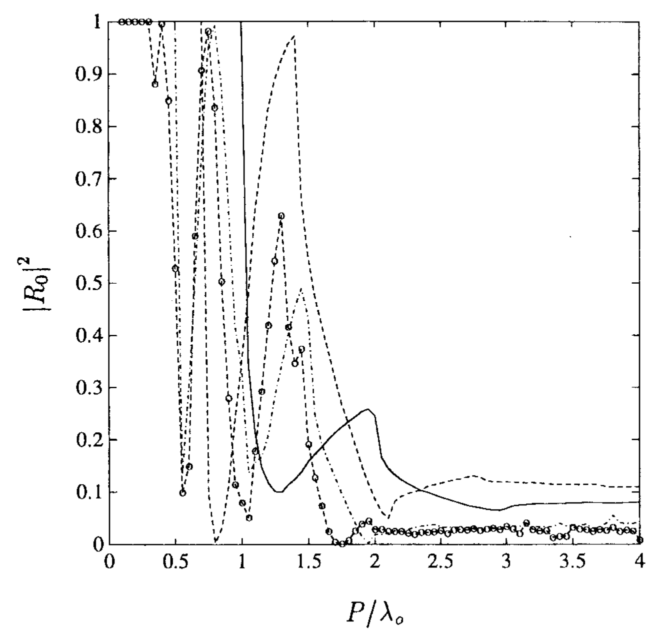

Fig. 3. Magnitude-squared of R_0 with a sinusoidal profile $y = -h + h\cos(2\pi x/P)$, $h = 0.25\lambda_o$, ——: $\epsilon_f = \epsilon_o$, - - -: $\epsilon_f = 2\epsilon_o$, -·-·-: $\epsilon_f = 4\epsilon_o$, - -o- -: $\epsilon_f = 9\epsilon_o$.

totally reflected back to the groove due to phase matching. Surface waves are thus formed and propagate in the $\pm x$ directions. This mechanism is similar to that of the surface wave modes in slab waveguides [9]. Quantitatively, with $\epsilon_f = \epsilon_{fr}\epsilon_o$, the surface waves start to propagate when $P/\lambda_o = 1/\sqrt{\epsilon_{fr}}$. This implies that for the same periodical surface, the reflected power curve starts to oscillate with frequecy at lower P/λ_o value if a higher permittivity cover is used. It is also observed that the reflected power also decreases at $P/\lambda_o > 2$ when the cover permittivity is larger than $4\epsilon_o$.

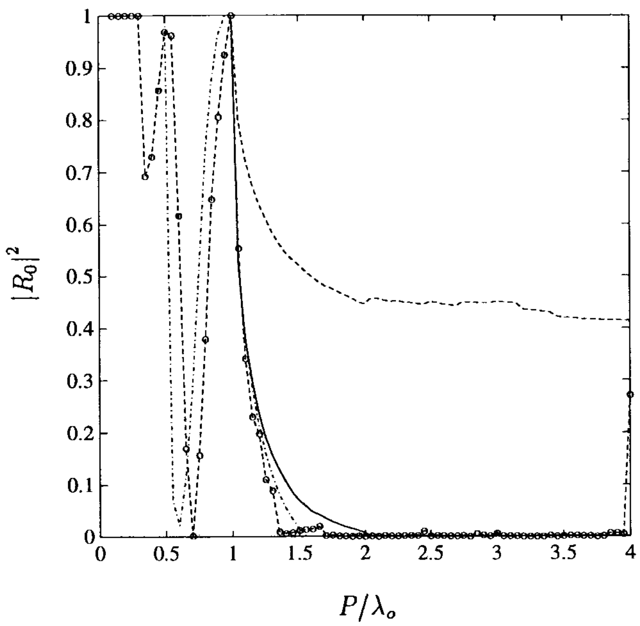

Fig. 4. Magnitude-squared of R_0 with a sawtooth profile $y = -(4h/P)x$ when $0 \le x \le P/2$, $y = (4h/P)(x - P)$ when $P/2 \le x \le P$, ——: $\epsilon_f = \epsilon_o$, $h = 0.25\lambda_o$, - - -: $\epsilon_f = \epsilon_o$, $h = 0.125\lambda_o$, —·—·—: $\epsilon_f = 4\epsilon_o$, $h = 0.25\lambda_o$, - -o- -: $\epsilon_f = 9\epsilon_o$, $h = 0.25\lambda_o$.

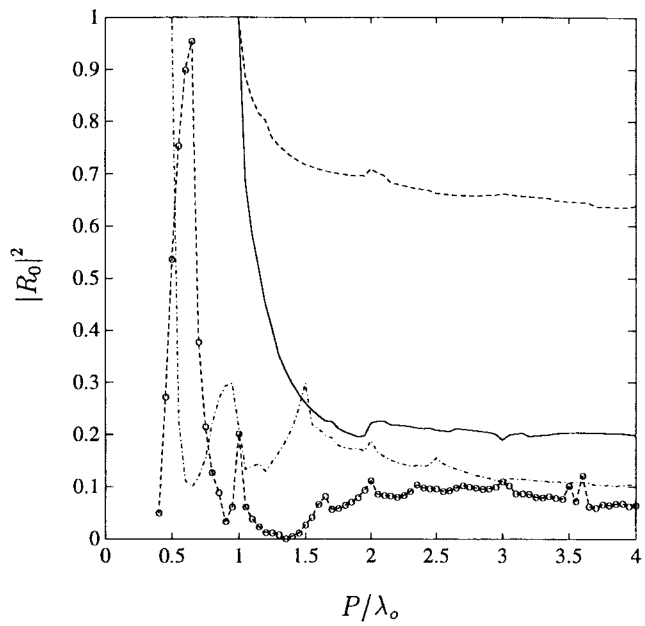

Fig. 5. Magnitude squared of R_0 with a convex elliptical profile $y = -2h + 2h(1 - 4x^2/P^2)^{1/2}$ when $-P/2 \le x \le P/2$, ——: $\epsilon_f = \epsilon_o$, $h = 0.25\lambda_o$, - - -: $\epsilon_f = \epsilon_o$, $h = 0.125\lambda_o$, —·—·—: $\epsilon_f = 4\epsilon_o$, $h = 0.25\lambda_o$, - -o- -: $\epsilon_f = 9\epsilon_o$, $h = 0.25\lambda_o$.

Fig. 4 shows the reflected power of a periodical surface with a sawtooth profile. This profile with $h = 0.25\lambda_o$ reflects smaller amount of power in the backward direction when $P/\lambda_o > 1.5$ except that a resonance peak occurs around $P/\lambda_o = 4$ when $\epsilon_f = 9\epsilon_o$. The reflected power in this frequency band is much lower than that with a sinusoidal profile. However, a shallower profile with $h = 0.125\lambda_o$ increases the reflected power significantly at higher values of P/λ_o. As was mentioned, the cover material reduces the frequency at which surface waves start to be guided in the $\pm x$ directions. Thus, the reflected power is reduced at certain frequencies in the $0 < P/\lambda_o < 1$ band in which the reflection coefficient is unity when without cover.

Fig. 5 shows the reflected power by convex elliptical periodical surfaces. The profile with $h = 0.125\lambda_o$ gives a much higher reflected power than that with $h = 0.25\lambda_o$. The reflected power with $h = 0.25\lambda_o$ in the frequency band $P/\lambda_o \ge 2$ is higher compared with that of the sinusoidal profile. The reflected power can be reduced when the cover permittivity is increased. Also notice that in the range $0.5 < P/\lambda_o \le 1$ and with $\epsilon_f = 4\epsilon_o$, the reflected power is significantly reduced compared with those of the sinusoidal and sawtooth profiles.

Fig. 6 shows the reflected power with a concave elliptical profile. The variations are similar to those in Fig. 5 except that the reduction of reflected power with P/λ_o is smoother in the range $1 < P/\lambda_o < 2$.

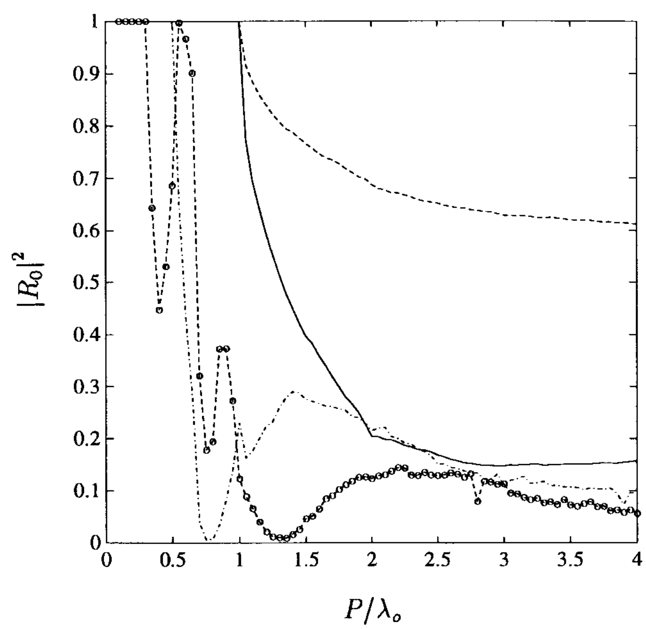

Fig. 6. Magnitude squared of R_0 with a concave elliptical profile $y = -2h[1 - 4(x - P/2)^2/P^2]^{1/2}$ when $0 \le x \le P$, ——: $\epsilon_f = \epsilon_o$, $h = 0.25\lambda_o$, - - -: $\epsilon_f = \epsilon_o$, $h = 0.125\lambda_o$, —·—·—: $\epsilon_f = 4\epsilon_o$, $h = 0.25\lambda_o$, - -o- -: $\epsilon_f = 9\epsilon_o$, $h = 0.25\lambda_o$.

IV. Conclusion

A mode-matching method has been developed to study the backscattering properties of periodical surface with dielectric cover when a TE plane wave is incident upon the surface normally. The use of dielectric cover reduces the frequency at which surface waves start to be guided, hence, reduces the reflected power at certain low frequencies in the $0 \le P/\lambda_o \le 1$ band at which total reflection occurs when without cover. The sawtooth profile with $h = 0.25\lambda_o$ reflects very little power at $P/\lambda_o \ge 2$ with or without cover. The sawtooth, concave, and convex elliptical profiles with $h = 0.125\lambda_o$ reflect a much higher power when $P/\lambda_o \ge 1$. For the sinusoidal, concave, and convex elliptical profiles, the addition of cover tends to reduce the backscattering power. The results obtained can be applied to reduce radar cross section of moving objects.

ACKNOWLEDGMENT

The author would like to thank the reviewers for their useful comments in revising this paper.

REFERENCES

[1] S. T. Peng, T. Tamir, and H. L. Bertoni, "Theory of periodic dielectric waveguides," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-23, pp. 123–133, Jan. 1975.
[2] H. L. Bertoni, L.-H. S. Cheo, and T. Tamir, "Frequency-selective reflection and transmission by a periodic dielectric layer," *IEEE Trans. Microwave Theory Tech.*, vol. 37, pp. 78–83, Jan. 1989.
[3] S.-L. Chuang and J. A. Kong, "Scattering of waves from periodic surfaces," *Proc. IEEE*, vol. 69, pp. 1132–1144, Sept. 1981.
[4] Y. Okuno and T. Matsuda, "Efficient technique for the numerical solution of diffraction by a Fourier grating," *J. Opt. Soc. Amer.*, vol. 4, pt. A, no. 3, pp. 465–472, Mar. 1987.
[5] K. A. Zaki and A. R. Neureuther, "Scattering from a perfectly conducting surface with a sinusoidal height profile: TE polarization," *IEEE Trans. Antennas Propagat.*, vol. AP-19, pp. 208–214, Mar. 1971.
[6] ——, "Scattering from a perfectly conducting surface with a sinusoidal height profile: TM polarization," *IEEE Trans. Antennas Propagat.*, vol. AP-19, pp. 747–751, Nov. 1971.
[7] S. D. Gedney, J. F. Lee, and R. Mittra, "A combined FEM/MoM approach to analyze the plane wave diffraction by arbitrary gratings," *IEEE Trans. Microwave Theory Tech.*, vol. 40, pp. 363–370, Feb. 1992.
[8] J. A. Kong, *Electromagnetic Wave Theory*, 2nd ed. New York: Wiley, 1990.
[9] R. F. Harrington, *Time-Harmonic Electromagnetic Fields*. New York: McGraw-Hill, 1993.

Jean-Fu Kiang (M'89) was born in Taipei, Taiwan, ROC, on February 2, 1957. He received the B.S.E.E. and M.S.E.E. degrees from National Taiwan University, and the Ph.D. degree from Massachusetts Institute of Technology, Cambridge, in 1979, 1981, and 1989, respectively.

He has worked at IBM Watson Research Center, Yorktown Heights, NY, from 1989 to 1990, Bellcore, Red Bank, NJ, from 1990 to 1992, and Siemens, Danvers, MA, from 1992 to 1994. He is currently with the Department of Electrical Engineering, National Chung-Hsing University, Taichung, Taiwan.