Progress In Electromagnetics Research B, Vol. 4, 223–235, 2008

INVESTIGATION ON THE SCATTERING CHARACTERISTICS OF GAUSSIAN BEAM FROM TWO DIMENSIONAL DIELECTRIC ROUGH SURFACES BASED ON THE KIRCHHOFF APPROXIMATION

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Abstract—The scattering characteristic of paraxial gaussian beam from two dimensional dielectric rough surfaces is studied in this paper. The modification of the Kirchhoff approximation theory for rough surface scattering by an incident gaussian beam instead of a plane wave are developed based on conventional Kirchhoff scattering theory and plane wave spectrum expansion method. The coherent and incoherent scattered intensity and cross section of two dimensional dielectric rough surfaces is derived in detail. As a application, under incidence wave length $\lambda = 1.06\,\mu\text{m}$, we calculate the coherent and incoherent scattered intensity and cross section of Gaussian beam scattering from plating aluminium dielectric rough surfaces change with the scattering zenith angles in different rough surface correlation length, rough surface height root mean square and other conditions. In the same scattering conditions, we compare the coherent and incoherent scattered section between the gaussian beam and plane wave to prove that our methods and programming cods is correct. The numerical results are shown that the incident gaussian beam size is much larger compared with the surface height correlation length, the normalized scattering cross section is the same as for an incident plane wave. The ratio between the beam size and the surface height correlation length play an important role in the scattering characteristic of the gaussian beam from two dimensional dielectric rough surfaces. The ratio is bigger, the coherent and scattered intensity and section is more remarkable and on the contrary the incoherent scattered intensity and section is relatively smaller.

1. INTRODUCTION

There has been an increasing interest in and need for investigation electromagnetic wave scattered from rough surface [1–4]. In recent years, with development of the laser technology, it is necessary to utilize the electromagnetic scattering theory and theoretically analyses the light scattering from a random rough surface [5, 6]. It is often assumed that the incident field is a plane wave for the simplification of the analyses that are obtained in [7, 8]. Dahl [9] has derived the geometric equations for Gaussian beams and discussed the characteristic of propagation on the Gaussian beams from a class of inhomogeneous anisotropic media. Wu and Guo [10] have utilized a new recursive algorithm to compute the scattering coefficients for multilayered cylinders arbitrarily located in a Gaussian Beam. On the other hand, in the numerical solution of the integral equations that govern scattering from rough surfaces, it is a common practice to assume that the incident field is a gaussian beam in order to limit the area of the rough surface that is illuminated. Collin [11] firstly discusses scattering of gaussian beam form perfectly conducting rough surfaces based on full wave method and draw a conclusion that when the incident gaussian beam has a plane phase front over the extent of the rough surface patch and the linear dimensions of the rough patch are larger compared with the surface height correlation length, the normalized incoherent scattering cross section is the same as for an incident plane wave, which gives support to the use of a taped illumination function in the numerical analysis of rough surface scattering. Shen and Dou [12] have discussed that Gaussian Beam Scattering from a Semicircular Channel in a Conducting Plane. Subsequently Chen [13] and Xue [14] has obtained the formula of the incoherent scattering cross section for dielectric rough surfaces using Kirchhoff scalar approximation. Chabory and Sokoloff et al. [15] apply the Gabor expansion to describe magnetic and electric currents given on a regular curved interface in dimension 2 by a new kind of gaussian beams. Notice that the results given in [11] and [14] are available for the incoherent scattering but not for the coherent scattering, which occurs when the surface standard deviation is small. The purpose of this paper is to determine the modifications required in the Kirchhoff scattering theory for rough surface for both coherent and incoherent scattering when the incident field is a gaussian beam instead of a plane wave. For the classical KA scattering theory, we will show that when the incident field is a gaussian beam the essential modifications required of the theory are a multiplication of the surface illumination function by a Gaussian illumination function and a change in the normalization factor that defines the normalized scattering cross-section and scattered intensity of the surface.

2. SCATTERING FIELDS OF OFF-AXIS GAUSSIAN BEAM BY TWO DIMENSIONAL DIELECTRIC ROUGH SURFACES

Consider a monochromatic gaussian beam TEM_{00} propagates along X_i axis in the homogeneous free space. The rough surface, with a profile $z' = z(x', y')$, and the incident gaussian beam are shown in Fig. 1. The reference coordinate system is $OXYZ$ and the beam coordinate system is $O_iX_iY_iZ_i$. The center of the beam waist is at the point $O_i(-x_0, 0, z_0)$. The distance from the beam waist center to the origin of the $OXYZ$ coordinate system is ρ_0. The incident beam axis is at an angle θ_0 with respect to the z axis.

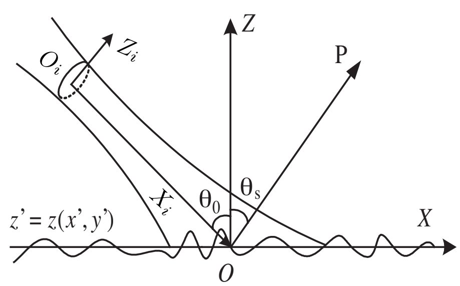

Figure 1. Geometry of Paraxial Gaussian beam scattering by rough surface.

We assume that the gaussian beam is the linear polarization on the beam waist plane and the electric field $\boldsymbol{E_i}(\boldsymbol{r_i})$ satisfies

$$\boldsymbol{E}(0, y_i, z_i) = \hat{\boldsymbol{y}}_{\boldsymbol{i}} E_0 \exp\left[-(y_i^2 + z_i^2)/w_0^2\right]. \tag{1}$$

Thus the incident gaussian beam is given by [16]

$$\boldsymbol{E}(x_i, y_i, z_i) = \frac{1}{4\pi^2} \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} \boldsymbol{f}(k_{yi}, k_{zi}) \exp(-i\boldsymbol{k_i} \cdot \boldsymbol{r_i}) dk_{yi} dk_{zi}, \tag{2}$$

where $k_{xi}^2 + k_{yi}^2 + k_{zi}^2 = k^2$, k is the free space wave number, w_0 is the beam waist radius, and

$$\boldsymbol{f}(k_{yi}, k_{zi}) = f(k_{yi}, k_{zi}) \left(-\frac{k_{yi}}{k_{xi}} \hat{\boldsymbol{x}}_{\boldsymbol{i}} + \hat{\boldsymbol{y}}_{\boldsymbol{i}} \right), \tag{3}$$

$$f(k_{yi}, k_{zi}) = \pi w_0^2 E_0 \exp\left[-\frac{(k_{yi}^2 + k_{zi}^2) w_0^2}{4} \right]. \tag{4}$$

When the statistical characteristics of the rough surface satisfy Kirchhoff approximation conditions, that is $kl > 6$, $l^2 > 2.76\sigma \cdot \lambda$ and the root-mean-square slope $s < 0.25$, where λ is the incident wavelength, σ is the surface standard deviation and l is the correlation length, the scattered filed of a plane wave spectrum can be expressed in the $OXYZ$ system [17]

$$E_{pq}^s = -\frac{ike^{-ikR}}{4\pi R} E_{q0}^i \int \bar{U}_{pq} \exp[-i\boldsymbol{k} \cdot (\boldsymbol{r'} - \boldsymbol{\rho_0})] \exp(i\boldsymbol{k_s} \cdot \boldsymbol{r'}) ds', \tag{5}$$

where $\bar{U}_{pq} = a_{pq0} + a_{pq1} Z_x + a_{pq2} Z_y$, Z_x or Z_y is the surface slope along x or y direction on the rough surface; E_{q0}^i is the incident electric filed amplitude, where $q = h, v$ corresponding to the component perpendicular to or parallel with the incident plane, given by

$$E_{h0}^i = \frac{1}{4\pi^2} \cdot \frac{\boldsymbol{f} \cdot (\boldsymbol{k_i} \times \hat{\boldsymbol{z}})}{|\boldsymbol{k_i} \times \hat{\boldsymbol{z}}|}, \quad E_{v0}^i = \frac{1}{4\pi^2} \cdot \frac{\boldsymbol{f} \cdot (\boldsymbol{k_i} \times \boldsymbol{k_i} \times \hat{\boldsymbol{z}})}{|\boldsymbol{k_i} \times \boldsymbol{k_i} \times \hat{\boldsymbol{z}}|}. \tag{6}$$

When we include the integration over the incident plane wave spectrum, the gaussian beam scattered field is found to be given by

$$\begin{aligned} E_{hh}^s = & -\frac{ik_0 e^{-ik_0 R}}{4\pi R} \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} dk_{yi} dk_{zi} \int \Big[\big(E_{h0}^i \alpha_{hh0} + E_{v0}^i \alpha_{hv0} \big) \\ & -\frac{v_x}{v_z} \left(E_{h0}^i \alpha_{hh1} + E_{v0}^i \alpha_{hv1} \right) \\ & - \frac{v_y}{v_z} \left(E_{h0}^i \alpha_{hh2} + E_{v0}^i \alpha_{hv2} \right) \Big] \exp\big[-ik_{xi} \big(x' \sin\theta_0 - z' \cos\theta_0 + \rho_0 \big) \\ & - ik_{yi} y' - ik_{zi} \left(x' \cos\theta_0 + z' \sin\theta_0 \right) \big] \exp\left(i\boldsymbol{k_s} \cdot \boldsymbol{r'} \right) ds'. \end{aligned} \tag{7}$$

To evaluate the integration over the incident plane wave spectrum, we assume that the beam waist center is far from the surface so that is large relative to the linear dimensions of the rough patch. This condition is easily met in most scattering experiments. With the above assumption, the stationary phase method is used and it is a relatively straightforward procedure to derive the following expression for the far zone hh polarization scattered field

$$\begin{aligned} E_{hh}^{s} &= \frac{k_0^2 w_0^2 E_0}{4\pi R\rho_0} e^{-ik_0(R+\rho_0)} S_{hh} \\ &\int_{-L}^{L}\int_{-L}^{L} \exp\left[-\frac{k_0^2 w_0^2}{4\rho_0^2}(x'^2\cos^2\theta_0 + y'^2)\right]\cdot \exp(i\boldsymbol{V}\cdot\boldsymbol{r}')ds', \end{aligned} \tag{8}$$

where $\boldsymbol{V} = \boldsymbol{k_s} - \boldsymbol{k}$, S is the polarization factor related with refractive index of rough surface and the incident and scattering directions. For other polarization scattered field, the expressions are the same with (8) only with different S, which have the following forms

$$\begin{aligned} S_{hh} = \frac{1}{2}\Big\{ & R_{\perp 0}(\cos\theta_0 + \cos\theta_s)\cos\phi_s + \frac{\sin\theta_s\cos\phi_s - \sin\theta_0}{\cos\theta_0 + \cos\theta_s} \\ & [R_{\perp 0}(\sin\theta_0 - \sin\theta_0\cos\phi_s) - R_{\perp 1}\cos\phi_s(\cos\theta_0 + \cos\theta_s)]\Big\}, \end{aligned} \tag{9}$$

$$\begin{aligned} S_{hv} = \frac{1}{2}\Big\{ & R_{//0}(1 + \cos\theta_0\cos\theta_s)\sin\phi_s - \frac{\sin\theta_s\cos\phi_s - \sin\theta_0}{\cos\theta_0 + \cos\theta_s} \\ & [R_{//0}\sin\theta_0\cos\theta_s + R_{//1}(1 + \cos\theta_0\cos\theta_s)]\sin\phi_s\Big\}, \end{aligned} \tag{10}$$

$$\begin{aligned} S_{vh} = \frac{1}{2}\Big\{ & R_{\perp 0}(1 + \cos\theta_0\cos\theta_s)\sin\phi_s - \frac{\sin\theta_s\cos\phi_s - \sin\theta_0}{\cos\theta_0 + \cos\theta_s} \\ & [R_{\perp 0}\sin\theta_0\cos\theta_s + R_{\perp 1}(1 + \cos\theta_0\cos\theta_s)]\sin\phi_s\Big\}, \end{aligned} \tag{11}$$

$$\begin{aligned} S_{vv} = \frac{1}{2}\Big\{ & R_{//0}(\cos\theta_0 + \cos\theta_s)\cos\phi_s + \frac{\sin\theta_s\cos\phi_s - \sin\theta_0}{\cos\theta_0 + \cos\theta_s} \\ & [R_{//1}(\cos\theta_s + \cos\theta_0)\cos\phi_s - R_{//0}(\sin\theta_s - \sin\theta_0\cos\phi_s)]\Big\}. \end{aligned} \tag{12}$$

3. THE COHERENT AND INCOHERENT SCATTERED INTENSITY AND SECTION OF TWO DIMENSIONAL DIELECTRIC ROUGH SURFACES AND ITS NUMERICAL RESULTS

According to Eq. (8), the coherent scattered intensity is derived

$$\begin{aligned} I_c \;=\; & \left|< E_{pq}^s >\right|^2 = \left|\frac{k_0^2 w_0^2 E_0}{4\pi R \rho_0} \cdot S_{pq}\right|^2 \\ & \cdot \iint \iint \exp\left\{-\frac{k_0^2 w_0^2}{4\rho_0^2}\left[(y'^2 + y''^2) + (x'^2 + x''^2)\cos^2\theta_0\right]\right\} \\ & \cdot \exp\left\{j\left[v_x(x' - x'') + v_y(y' - y'')\right]\right\} \cdot < \exp(jv_z \cdot z') > \\ & \cdot < \exp(-jv_z \cdot z'') > ds' ds''. \end{aligned} \tag{13}$$

Using variables transform and the property of gaussian rough surface that $< \exp(jv_z z) >= \exp(-\sigma^2 v_z^2/2)$, we obtain

$$\begin{aligned} I_c = & \left|< E_{pq}^s >\right|^2 \\ = & \left(\frac{k_0 w_0 E_0}{4\pi R}\right)^2 \cdot \frac{2\pi \left|S_{pq}\right|^2}{\cos\theta_0} \cdot \int_{-2L}^{2L}\int_{-2L}^{2L} \exp\left[-\frac{k_0^2 w_0^2}{8\rho_0^2}(x_d^2\cos^2\theta_0 + y_d^2)\right] \\ & \cdot \left\{1 - erfc\left[\frac{k_0 w_0}{\sqrt{8}\rho_0}(2L - |x_d|)\cos\theta_0\right]\right\} \cdot \left\{1 - erfc\left[\frac{k_0 w_0}{\sqrt{8}\rho_0}(2L - |y_d|)\right]\right\} \\ & \cdot \exp[j(v_x \cdot x_d + v_x \cdot y_d)] \cdot \exp(-\sigma^2 \cdot v_z^2) dx_d dy_d, \end{aligned} \tag{14}$$

where $erfc(y) = \frac{2}{\sqrt{\pi}} \int_y^{+\infty} e^{-t^2} dt$ represents the complementary error function.

We now assume that at the edge of the rough surface patch, the beam illumination is very small. From an examination of Eq. (14), we see that we require $L\cos\theta_0/w$ to be at least as large as 2, where w is the beam size defined by $2\rho_0/k_0 w_0$. Hence the arguments of the complementary error function are at least as large as 2.8 and the complementary error function is negligible relative to unity for small values of x_d and y_d. With the increase of values of x_d and y_d, the beam illumination function decreases quickly and the integrand in Eq. (14) vanishes, thus only values of x_d and y_d that are small relative to L will give significant contributions to the scattered intensity.

Under the condition given above the expression for the coherent scattered intensity reduces to the following simple form

$$I_c = \left(\frac{k_0 w_0 E_0}{4\pi R}\right)^2 \cdot \frac{2\pi |S_{pq}|^2}{\cos\theta_0} \cdot \frac{2\pi w^2}{\cos\theta_0} \cdot \exp\left(-\sigma^2 \cdot v_z^2\right) \cdot \exp\left[-\frac{w^2}{2}\left(v_x^2/\cos^2\theta_0 + v_y^2\right)\right] \tag{15}$$

The incident gaussian beam is readily evaluated using the stationary phase method. It is given by [13]

$$\boldsymbol{E_q^i} = \boldsymbol{a_i} j k_0 \pi w_0^2 E_0 \frac{e^{-jk_0\rho_0}}{2\pi\rho_0} \exp\left[-\frac{k_0^2 w_0^2}{4\rho_0^2}\left(x^2\cos^2\theta_0 + y^2\right)\right] \cdot \exp\left[-jk_0\left(x\sin\theta_0 - z\cos\theta_0\right)\right] \tag{16}$$

where $\boldsymbol{a_i}$ is the unit polarization vector in the beam coordinate system. With the above equation, the total power of the incident field on the illuminated surface is written as

$$P_i = \int_{-L}^{+L}\int_{-L}^{+L} \left|\vec{E}^i\right|^2 dx'dy' = \frac{\pi w_0^2 E_0^2}{2\cos\theta_0} \tag{17}$$

According to the definition of Thorsos for the scattering cross section [10], the normalized coherent scattering cross section of the incident gaussian beam field is given by

$$\sigma_{pqc}^0 = \frac{4\pi R^2 \cdot I_c}{P_i} = \frac{2k_0^2 w^2}{\cos\theta_0} \cdot |S_{pq}|^2 \cdot \exp\left(-\sigma^2 \cdot v_z^2\right) \cdot \exp\left[-\frac{w^2}{2}\left(v_x^2/\cos^2\theta_0 + v_y^2\right)\right]. \tag{18}$$

Compared the above expression with that for a plane wave, we found that for the gaussian beam, the contribution to the coherent scattering comes form the region around the specular direction and the angular width is related with the beam size, but for the case of plane wave incidence, the Kirchhoff scalar result shows that the contribution only occurs in the specular direction. Fig. 2 calculates the dependence of bistatic σ_{pqc}^0 for HH polarization on beam size, with $\theta_0 = 0$, $\phi_s = 0$, $\lambda = 1.06\,\mu\text{m}$, $\sigma = 0.1\lambda$, $l = \lambda$ and the refractive index $n = 2.43 + i10.7$. It is shown that the angle width of σ_{pqc}^0 decreases as beam size increases, which means the coherent scattered intensity more focuses in the specular direction as the incident field approaches to the plane wave. In Fig. 3, the specular results for the gaussian beam and the plane wave are compared for 0–40 degree incident angles. When the beam size is much larger than the surface height correlation length, σ_{pqc}^0 is almost the same for two cases.

The normalized incoherent scattering cross section for gaussian beam is derived

$$\sigma_{pqi}^0 = \frac{k_0^2}{\pi} \cdot |S_{pq}|^2 \cdot \int_{-2L}^{2L} \int_{-2L}^{2L} \exp\left(-\frac{x_d^2 \cos^2\theta_0 + y_d^2}{2w^2}\right) \cdot \exp(-\sigma^2 v_z^2)$$
$$\cdot \left\{\exp[\sigma^2 v_z^2 c(\tau)] - 1\right\} \cdot \exp[j(v_x x_d + v_y y_d)] dx_d dy_d, \qquad (19)$$

where $c(\tau)$ is the height correlation function and $\tau = \left(x_d^2 + y_d^2\right)^{1/2}$ stands for the distance between two points on the rough surface.

We can see that since the existence of the term $\{\exp[\sigma^2 v_z^2 c(\tau)] - 1\}$, only small values of x_d and y_d with respect to L give significant contributions to the incoherent scattering cross section because $c(\tau)$ becomes very small for τ greater than a few correlation lengths. When the beam size is much larger than surface height correlation length, the illumination function in Eq. (19) is close to one, which leads to the incoherent scattering cross section as the same as that for an incident plane wave. Because the condition mentioned above normally occurs in practice, a taped plane wave (paraxial gaussian beam) is used commonly instead of a plane wave in the rough surface scattering numerical calculations fro many researchers [14–16].

Let us make a comparison of the results for gaussian beam and plane wave. Suppose the roughness parameters $\sigma = 0.2\,\mu\text{m}$, $l = 2.7\,\mu\text{m}$ and other conditions is the same as Fig. 2 and Fig. 3 do. Fig. 4 and Fig. 5 calculate the backscattering and bistatic scattering for HH polarization, respectively. From the results we can see that for larger beam size there is little different with two cases, but for small beam size ($w = l$) the difference is clear, which means the approximation of plane wave with a thin incident beam is not suitable, an agreement with the conclusion of literature [10]. Fig. 6 and Fig. 7 respectively calculate the effect of beam size on the normalized coherent and incoherent bistatic scattered intensity. From the results, we find that the effect of beam size on the normalized coherent and incoherent bistatic scattered intensity are consistent with their coherent and incoherent scattered intensity and cross section.

In the course of derivation and computation, noticed that under the Kirchhoff scalar approximation $\sigma^2 v_z^2$ is a small quality, so the factor $\exp[\sigma^2 \cdot v_z^2 \cdot c(\tau)]$ in Eq. (8) can be expanded as an infinite series. With the assumption that the linear dimension of the illuminated surface patch is much larger than the correlation length, there is no significant

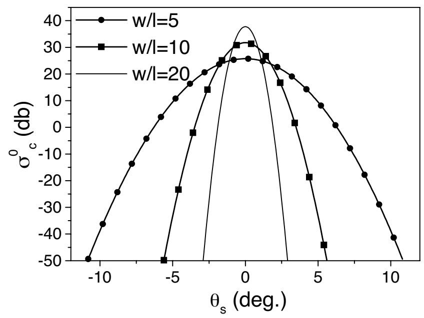

Figure 2. Dependence of the normalized bistatic coherent scattering cross section on the beam size.

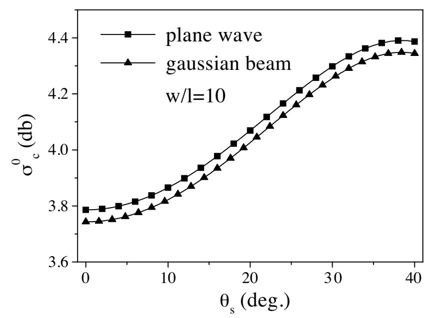

Figure 3. Comparison of the normalized coherent scattering cross section in the specular direction.

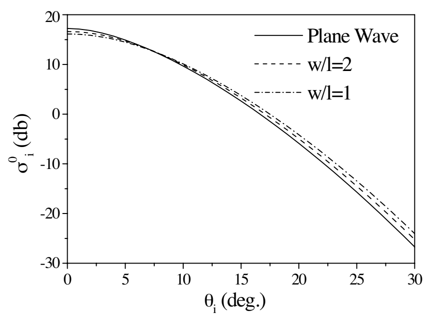

Figure 4. The effect of beam size on the normalized incoherent backscattering cross section.

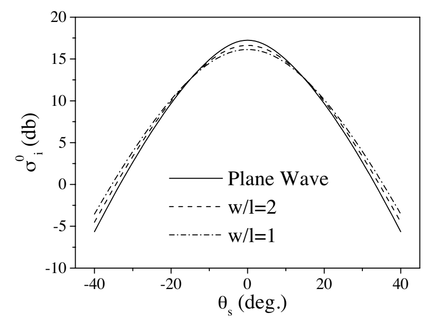

Figure 5. The effect of beam size on the normalized incoherent bistatic scattering cross section.

error introduced by extending the integral limits to infinite. Then Eq. (19) will be written as

$$\sigma_{pqi}^0 = (k_0 l)^2 \cdot |S_{pq}|^2 \cdot \exp(-\sigma^2 v_z^2) \cdot \sum_{n=1}^{\infty} \frac{\left(\sigma^2 v_z^2\right)^n}{n! \cdot n} \cdot \left[\left(1 + \frac{l^2 \cos^2\theta_0}{2n \cdot w^2}\right) \cdot \left(1 + \frac{l^2}{2n \cdot w^2}\right)\right]^{-\frac{1}{2}} \cdot \exp\left[-v_x^2 l^2 \Big/ 4n\left(1+\frac{l^2\cos^2\theta_0}{2n\cdot w^2}\right)\right] \cdot \exp\left[-v_y^2 l^2 \Big/ 4n\left(1+\frac{l^2}{2n\cdot w^2}\right)\right]. \quad (20)$$

When the condition that $l^2 \ll 2w^2$ holds, the incident beam

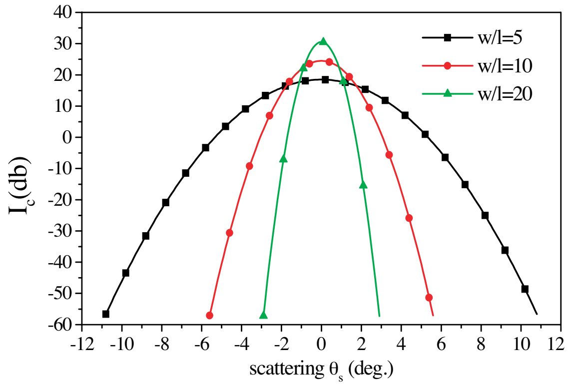

Figure 6. The effect of beam size on the normalized coherent bi-static scattered intensity.

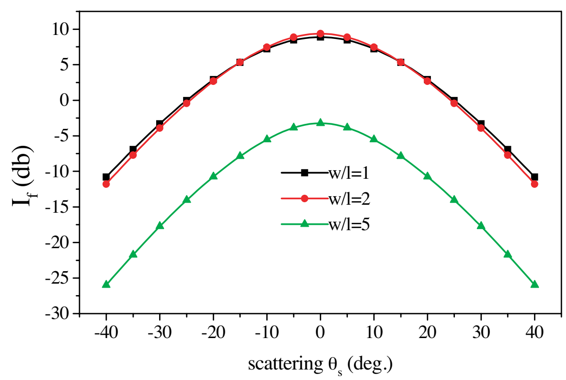

Figure 7. The effect of beam size on the normalized incoherent bi-static scattered intensity.

illumination function is close to one, and the relevant terms can be negligible in Eq. (20). Substituting the detailed expression of the polarization factor $|S_{pq}|^2$ into Eq. (20), we obtain

$$\sigma_{pqi}^0 = \frac{(k_0 l)^2}{4} \cdot \exp(-\sigma^2 v_z^2) \cdot \left[|a_0|^2 - 2\mathrm{Re}\left\{ \frac{v_x}{v_z} a_0 a_1^* \right\} + |a_1|^2 \cdot \frac{v_x^2}{v_z^2} \right] \cdot \sum_{n=1}^{\infty} \frac{(\sigma^2 v_z^2)^n}{n! \cdot n} \cdot \exp\left[-(v_x^2 + v_y^2) \cdot l^2 / 4n \right]. \quad (21)$$

Comparison of the above equation with the normalized incoherent scattering cross section in literature [17], given by

$$\sigma_{pqi}^0 = \frac{(k_0 l)^2}{4} \cdot \exp\left(-\sigma^2 v_z^2\right) \cdot \left[|a_0|^2 - 2\mathrm{Re}\left\{\frac{v_x}{v_z} a_0 a_1^* + \frac{v_y}{v_z} a_0 a_2^*\right\}\right] \cdot \sum_{n=1}^{\infty} \frac{\left(\sigma^2 v_z^2\right)^n}{n! \cdot n} \cdot \exp\left[-(v_x^2 + v_y^2) \cdot l^2/4n\right], \quad (22)$$

and notice that the term a_2 in Eq. (22) is zero while let $\phi = 0$. In addition, we consider the polarization contribution of surface slop term, corresponding to the third term in square bracket in Eq. (21), if neglected it our results can reduce to the case for a plane wave.

4. CONCLUSION

In this paper, the scattering of paraxial gaussian beam by two dimensional dielectric random rough surfaces is discussed in detail. Based on Kirchhoff scalar scattering theory and plane wave spectrum expansion method, and the formula of the normalized coherent scattering cross section is derived with the linear dimension of rough surface patch larger twice than the ratio of the beam size to the incident angle cosine. Under incidence wave length $\lambda = 1.06\,\mu\mathrm{m}$, we calculate the coherent and incoherent scattered intensity and section of Gaussian beam scattering from plating aluminium dielectric rough surfaces change with the scattering zenith angles in different rough surface correlation length, rough surface height root mean square and other conditions. In the same scattering conditions, we compare the coherent and incoherent scattered section between the gaussian beam and plane wave to prove that our methods and programming cods is correct. The numerical results are shown that $w > l$, the normalized scattering cross section is the same as for an incident plane wave. The ratio w/l plays an important role in the scattering characteristic of the gaussian beam from two dimensional dielectric rough surfaces. The ratio is bigger, the coherent and scattered intensity and section is more remarkable and on the contrary the incoherent scattered intensity and section is relatively smaller.

ACKNOWLEDGMENT

This works is supported by the National Nature Foundation of China under Grant No. 60771038 and 60741003. J. Wang is the author to whom the correspondence should be addressed, his e-mail address is wmjxd@yahoo.com.cn.

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