SPACE AND TIME DISTORTION OF REFLECTED BEAM DUE TO SURFACE-ELECTROMAGNETIC-WAVE GENERATION FOR GRAZING INCIDENCE ON METAL GRATING

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Specular reflection is examined for grazing incidence of a beam of pulsed laser radiation on a periodic grating under conditions of surface-electromagnetic-wave (SEW) generation with diffraction order l = -1. It is shown that reradiation of the SEW energy in the reflection direction and beam spreading can greatly affect the shape of the reflected signal.

INTRODUCTION

As is known [1], the excitation of surface electromagnetic waves (SEW) when radiation interacts with metals can result in a number of interesting physical phenomena. One is that of the total cancellation of metal reflection, which is realized with gratings with a certain optimum profile depth in resonance SEW excitation by a plane monochromatic wave [2, 3]. The situation has been studied [4, 5] in which SEW excitation by metal gratings is accomplished by pulsed laser radiation whose beam width and pulse duration are comparable with the SEW free path and lifetime, respectively. In this case, however, the space and time distortions of the reflected signal are strong. In the earlier examinations [4, 5], the angle of incidence Y of the radiation satisfied the condition cos Y ~ 1.

Here we shall investigate the case of grazing incidence (cos Y << 1) on a metal grating. In this case, SEW excitation by a plane monochromatic wave has a specific nature [6], which manifests itself as a considerable change in the characteristic resonance parameters as compared with the case of cos Y ~ 1. It will be shown below that for SEW excitation by beams of pulsed laser radiation, this quantitative difference leads to qualitatively new results.

The calculations were performed for narrow beams assuming that the wavelength \( \lambda \) was small in comparison with the transverse dimension of the beam of incident radiation \( R \), i.e.,

\[
\frac{\lambda}{R} \ll 1.
\]

A preliminary report on the results of this work was presented elsewhere [7].

1. DERIVATION OF MAIN FORMULAS

For simplicity, we shall examine situation in which the incident radiation has p-polarization, the reciprocal-grating vector \( \vec{g} \) lies in the plane of incidence, and the grating has a sinusoidal profile. Here, \( \omega_0 \) is the carrier frequency, \( k_0 = \omega_0/c \) is the corresponding wave vector, and \( c \) is the velocity of light in vacuum. For solution of the problem, the incident field and specular reflection will be represented as Fourier expansions in the wave vectors \( \vec{k} \) and frequencies \( \omega \). The electric-field strengths of the partial waves, the incident wave \( \vec{E}_0(\vec{k}, \omega) \), and its specular reflection \( \vec{E}(\vec{k}', \omega) \) for resonance SEW excitation with diffraction order \( l = -1 \) are related as follows [6]:

\[ E'(\vec{k}', \omega) = F(\vec{k}, \omega)E_0(\vec{k}, \omega), \]  
where
\[
F(\vec{k}, \omega) = \frac{W - \zeta - \frac{2W}{(W + \zeta)^2} \frac{\epsilon^2}{W_{-1} + \zeta + \frac{W_{+1}^2}{W + \zeta}}}{W = W(\vec{k}, \omega)} = \frac{1}{k} \sqrt{k^2 - (\vec{k} - \vec{n}(\vec{n} \vec{k}))^2}, \]

\[ W_{-1}(\vec{k}, \omega) = W(\vec{k} - \vec{g}, \omega), \]
k = |\vec{k}| = |\vec{k}'| = \omega/c, \vec{k}' = \vec{k} - 2\vec{n}(\vec{n} \vec{k}), \vec{n} is the inward normal to the unperturbed metal surface, \( \zeta = \zeta' - i\zeta'' \) is the surface impedance, \( \epsilon = \beta g/2 \) is the amplitude of the grating profile, and \( g = |\vec{g}| = 2k_0 \).

The space–time structure of the reflected field is greatly dependent on the relationship between the grazing angle \( \alpha = \pi/2 - \gamma \) and the diffraction divergence angle \( \alpha_d = 1/k_0 R \). We shall examine the two limiting cases of \( \alpha >> \alpha_d \) and \( \alpha << \alpha_d \).

Satisfaction of the inequality \( \alpha >> \alpha_d \) corresponds to the situation of geometrical optics in which diffraction divergence is practically absent in the process of radiation reflection. In this case, we can employ the concept of an irradiation spot whose area corresponds to the intersection of the laser beam with the metal surface. The inequality \( \alpha_d << \alpha \) guarantees that diffraction divergence is insignificant over the length of the spot. The functional dependence of the reflected-radiation field on the coordinates and time is derived from formula (2) by an inverse Fourier transform. As variables of integration it is convenient to take \( \Delta \omega = \omega - \omega_0 \) and the components of the two-dimensional vector \( \vec{x} \), which corresponds to the projection of the wave vector \( \vec{k} \) onto the plane of the incident beam’s cross-section. Considering that \( |\vec{x}| \leq 1/R \), to calculate the reflected-radiation field \( E' \) at distance \( u \) on the beam path from the control cross-section of the incident beam, which satisfies the inequality \( u \ll k_0 R \)

\[ u \ll k_0 R^2 \]  
with accuracy to \( -\alpha_d/\alpha << 1 \), the contribution that is linear with respect to \( \vec{x} \) under the radical sign and quadratic in \( W_{-1} \) should be ignored when substituting (4) into (3). Calculations yield

\[ E'(\vec{v}, u, t) = e^{i(k_0 u - \omega_0 t)} \left\{ \frac{\alpha - \zeta}{\alpha + \zeta} E_0 \left( \vec{v} - 2\vec{n}(\vec{n} \vec{v}), 0, t - \frac{u}{c} \right) + \epsilon \left( \vec{v}, t - \frac{u}{c} \right) \right\}, \]

where

\[ \epsilon(\vec{v}, t) = -\frac{2\alpha^2}{(\alpha + \zeta)^2} \int_0^\infty ds e^{i\Delta s} f(s, \zeta)E_0 \left( \vec{v} - 2\vec{n}(\vec{n} \vec{v}) + 2\vec{n} \frac{s}{k_0}, 0; t - \frac{4s}{\omega_0} \right), \]

\[ \Delta = W_{-1}(\vec{k}_0, \omega_0), \vec{v} \] is a two-dimensional radius vector in the beam cross-section read from the beam axis, and \( E_0(\vec{v}, 0; t) \) is the field distribution in the control cross-section of the incident beam for \( u = 0 \). The function \( \epsilon(\vec{v}, t) \) corresponds to the electric field reradiated by the SEW in the reflection direction. The function \( f(s, \zeta) \), which is defined by the relations

\[ f(s, \zeta) = i\zeta \left[ e^{\frac{p^2}{2\epsilon}} \text{erfc}(p) - \frac{1}{\sqrt{\pi p}} \right], \]

\[ \zeta = \zeta + \frac{\epsilon^2}{\alpha + \zeta}, \quad p = e^{-i\frac{1}{4} \epsilon^2 s}\sqrt{s}, \quad \text{erfc}(p) = \frac{2}{\sqrt{\pi}} \int_p^\infty dp_1 e^{-p_1^2}, \]

has the following limit expressions:

\[ f(s, \zeta) \approx \frac{e^{-i\frac{1}{4} \epsilon^2 s}}{\sqrt{\pi s}}, \quad s|\zeta|^2 < 1, \]

\[ f(s, \zeta) \approx 2i\zeta e^{i\frac{1}{2}s} \Theta(-\text{Im}(\zeta e^{i\frac{1}{2}})) + \frac{e^{i\frac{1}{4} \epsilon^2 s}}{2\sqrt{\pi \epsilon^2 s^{3/2}}}, \]