Detection of a surface current during the reflection of light from a diffraction grating

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A current flow along the surface of a diffraction grating has been detected during the reflection of a laser pulse from the grating. It is suggested that this effect is a consequence of radiation pressure.

1. The absorption of light in a semiconductor is known to give rise to a current, as a result of the transfer of momentum from the absorbed photons to free charge carriers. An attempt to experimentally observe an analogous effect upon the reflection of light from a conducting metal surface would be worthwhile.

In the case of specular reflection, radiation pressure evidently does not give rise to a significant electric current, since the electrons are partially forced into the interior of the metal, and further motion of these electrons is stopped by the polarization electric field that arises. However, there may be cases in which radiation pressure can excite a surface current. Specifically, let us examine the particular case of the reflection of light with $\lambda = 1.06\ \mu\text{m}$ from a diffraction grating with a line spacing $d = 0.83\ \mu\text{m}$ (1200 lines/mm). In this case the pattern of the image reflection is as shown in Fig. 1, and the reflection condition is $\sin\alpha + \sin\beta = \lambda/d = 1.27$. In this case, in contrast with specular reflection, there is evidently a change in not only that component of the momentum of the incident light which is perpendicular to the reflecting surface ($P_\perp$) but also in the momentum component which is parallel to the surface ($P_\parallel$). There should apparently also be a change in that component of the momentum of the electrons which are participating in the reflection of the light that is parallel to the surface. In other words, the electrons should begin to move in the direction opposite the momentum component $P_\parallel$ acquired by the light. As Fig. 1 shows, the change in $P_\parallel$ is

$$\Delta P_\parallel = \frac{\mathscr{E}}{c}\sin\alpha + \frac{\mathscr{E}}{c}\sin\beta = \frac{\mathscr{E}}{c}\frac{\lambda}{d} \tag{1}$$

where $\mathscr{E}$ is the energy of the light pulse. The force exerted on an electron along the surface of the metal can be estimated from $F \sim \Delta P_\parallel / ab\delta n\tau$, where a and b are the dimensions of the light beam along and across $P_\parallel$, δ is the depth to which the light penetrates into the metal ($\delta \sim 10^{-6}$ cm for $\lambda \sim 10^{-4}$ cm; Ref. 2), n is the density of free electrons, and τ is the length of the light pulse. We then find the following expression for the voltage along $P_\parallel$:

$$U \sim W / cb\delta ne \tag{2}$$

where W is the power of the light pulse. An estimate for a light pulse with $\mathscr{E} = 3$ J and $\tau = 40$ ns with $n = 2 \times 10^{23}\ \text{cm}^{-3}$, $\delta \sim 10^{-6}$ cm, and $b = 4$ cm yields $U \sim 2 \times 10^{-2}$ V.

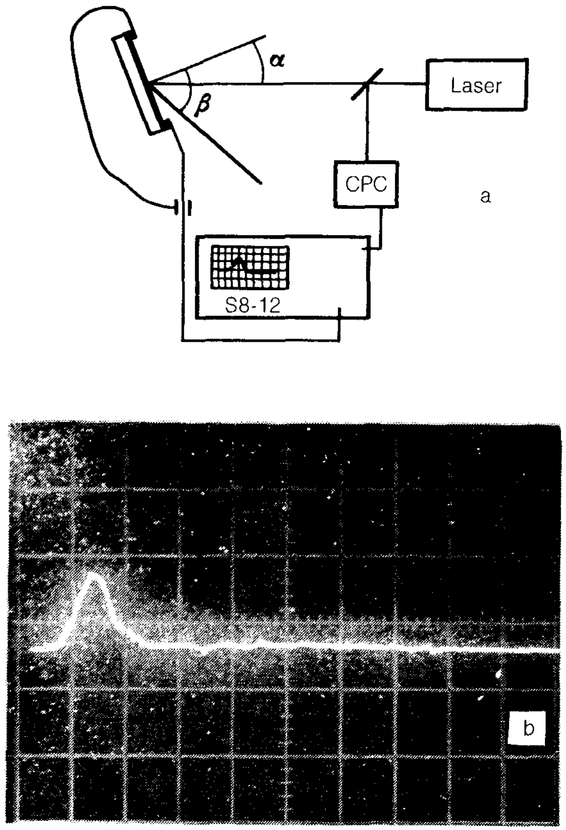

FIG. 1. a—Experimental layout (CPC is a coaxial photocell); b—oscilloscope trace of the voltage pulse (the sweep is 50 ns/div).

To estimate the magnitude of the current flowing along the surface, we should allow for the fact that the layer in which the emf is acting in this case ($\sim 10^{-6}$ cm) is significantly thinner than the thickness of the lower-lying metal layer, γ, along which the current is short-circuited. For a diffraction grating, the value of γ may be determined by the thickness of the metal layer holding the lines, but it cannot exceed the thickness of the skin layer, which determines the duration of the reflected laser pulse (at $\tau \sim 40$ ns, we would have $\gamma \sim 10^{-3}$ cm). We can apparently conclude that the current will be limited by the resistance of the layer of thickness δ: $R \sim (\rho a/b\delta) \sim (\rho/\delta) \sim 3\ \Omega$, where ρ is the resistivity (we have used the value of ρ for aluminum). We then find the current to be $J \sim 10^{-2}$ A. Measurements have shown that the thickness of the metal layer in the gratings used in the experiments described below is 2×10^{-4} cm, and its resistance is $r \sim 10^{-2}\ \Omega$. The current which is excited at the surface will then evidently be short-circuited, and in the measurements we should detect a voltage $Jr \sim 10^{-4}$ V across a 50-Ω load.

2. In the experiments we use a GOS-1001 laser equipped with a passive Q modu-

lator, which eliminates electromagnetic stray pickup at the time at which the laser operates. The maximum energy reaches 10 J in a pulse 40 ns long. We study the reflection from diffraction gratings with 1200 lines/mm. For the detection we use a UZ-33 wide-band amplifier (gain$\approx$10) and an S8-12 storage oscilloscope. A photocell is used to synchronize events. When a grating with a transverse dimension of 40 mm is illuminated by a pulse with an energy of 3 J, we detect a voltage pulse of 30 mV at the diffraction grating. The polarity and length of this voltage pulse correspond to the picture drawn above (Fig. 1b). The magnitude found experimentally for the signal is thus about two orders of magnitude greater than that predicted on the basis of purely classical considerations with allowance for the short-circuiting. This result seems to show that not all of the conduction electrons but only a comparatively small fraction of them are participating in the process [see expression (2)]. The effect of the energy of the laser pulse on the signal strength is studied by attenuating the light with precalibrated optical filters. Within the measurement errors, the dependence is linear (Fig. 2a). Figure 2b shows the dependence on the angle of incidence of the light. It follows from (1) that the strength of the signal should not depend on the angle of incidence. In reality, however, in order to find the magnitude of the signal it is necessary to find the projection of the change in the momentum of the light onto the surface of the lines which are participating in their reflection and along which the current flows (Fig. 3a), rather than the projection onto the surface of the grating.

3. We carrier out several control experiments: a) In the case of reflection from a metal mirror, there was no signal. b) When the light passed through a glass plate, there was no signal (we observed a random pickup because of the breaking of the circuit). c) We changed the electrodes (Fig. 3b). d) To test the validity of the conclusions regarding the effect of the short-circuiting on the results of the voltage measurements, we fabricated a diffraction grating with a metal layer with a thickness of $(0.5\text{–}1)\times 10^{-5}$ cm. The corresponding experiment confirmed the picture drawn above and revealed that the signal increased to a level of twenty times that for the gratings originally used.

4. Since the experiments showed that the observed phenomenon cannot be explained in a purely classical picture, so that it is apparently necessary to appeal to quantum-mechanical ideas (the Compton effect; see also Ref. 3), we wish to see whether there is a slight shift in the wavelength of the light reflected from the grating.

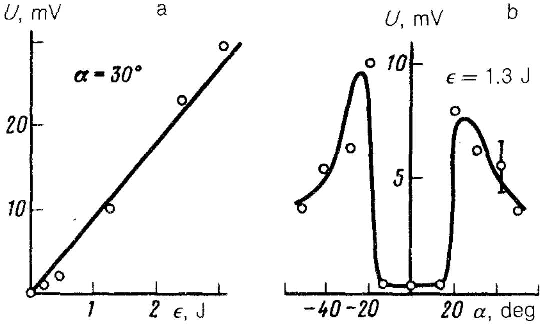

FIG. 2. a—Strength of the signal versus the energy of the laser pulse; b—strength of the signal versus the angle of incidence on the grating.

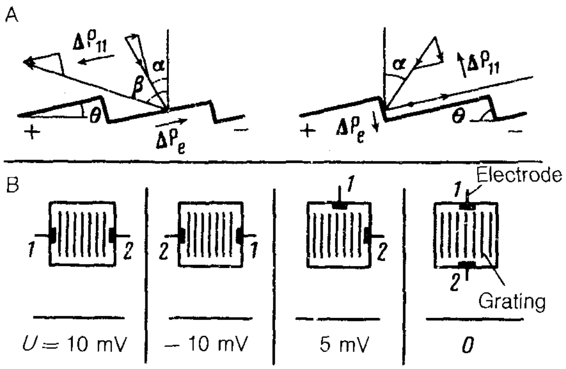

FIG. 3. a—Effect of the shape of the grating lines on the polarity of the signal; b—effect of the electrode arrangement on the strength of the signal.

The magnitude of this shift in the scattering of a photon by a free electron is $\sim 10^{-2}$ Å, which corresponds to $\sim 10^9$ Hz for the visible range. For this experiment we assembled a Michelson interferometer, using as light source a He–Ne laser with an output linewidth of less than 10^5–10^6 Hz. The diffraction grating was placed in one arm of this interferometer. If the wavelength shift exceeded the linewidth of the laser output, we would evidently not be able to visually observe an interference at the exit from the interferometer. However, an interference was found, so that the shift of the wavelength—if it occurred—did not exceed 10^5–10^6 Hz.

5. In summary, these experiments have revealed that a surface current is excited upon the reflection of an intense laser pulse (up to 10^7 W/cm^2) from a diffraction grating. The magnitude of the effect has been shown to be two orders of magnitude greater than that predicted by classical estimates. In the reflection of the light from the He–Ne laser from the grating, there is no wavelength shift; i.e., at a low light intensity, the effect is not a quantum-mechanical effect. The following might be offered as a hypothesis for explaining these results: At a light intensity $\sim 10^6$ W/cm^2, "hot electrons" are known to arise in metals because of a stepwise multiphoton excitation of electrons.[4] It can apparently be suggested that the appearance of a current upon the reflection of an intense laser pulse from a diffraction grating and the magnitude of this current are determined by the participation of hot electrons in the process.

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[1] A. M. Danishevskiĭ, A. A. Kastal'skiĭ, E. M. Ryvkin, and I. D. Yaroshetskiĭ, Zh. Eksp. Teor. Fiz. **58**, 441 (1970) [Sov. Phys. JETP **31**, 234 (1970)].

[2] M. Born and E. Wolf, Principles of Optics, Pergamon Press, New York, 1959 (Russ. transl. Nauka, Moscow, 1973).

[3] A. V. Sokolov, Opticheskie svoĭstva metallov (Optical Properties of Metals), GIFML, Moscow, 1961, p. 113.
[4] A. V. Ben'kov, A. V. Zinov'ev, and V. B. Lugovskoĭ, Pis'ma Zh. Tekh. Fiz. **6**, 1456 (1980) [Sov. Tech. Phys. Lett. **6**, 628 (1980)].

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