Thermal radiation of periodic metal surfaces

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The thermal radiation of metal diffraction gratings with various periods and groove depths has been studied experimentally. Peaks are found in the spectral emissivity under conditions corresponding to Wood's anomalies.

The interactions of electromagnetic radiation with periodic surfaces are the subject of a rapidly developing branch of optics. Interest in the problem dates back to the beginning of the century, when Robert Wood[1] discovered anomalies in the diffraction of electromagnetic radiation by diffraction gratings. Since then, this problem has been the subject of a large number of theoretical and experimental studies.[2,3] Under conditions such that Wood's anomalies are manifested, a resonant excitation of surface electromagnetic waves occurs. This wave excitation alters the course of physical processes at the surface of grating. In particular, it has been predicted that specular reflection would be completely suppressed[4] and that the incident radiation would be absorbed essentially completely[5,6] during resonant excitation of surface electromagnetic waves.

Studies carried out in the mid-IR region have shown that the gratings have sharp, narrow absorption peaks. One might expect that the anomalies resulting from the resonant excitation of surface electromagnetic waves would also be present in the thermal radiation of periodic surfaces. To the best of our knowledge, there has been no theoretical study of this problem. In this letter we are reporting an experimental study of the thermal radiation from diffraction gratings.

We briefly recall that Wood's anomalies in the angular distribution of the absorption coefficient of a metal grating are observed at resonant angles of incidence θ_0 (Refs. 2 and 3):

$$\theta_{0P} \simeq \arcsin|1 - l\lambda/d|, \quad P\text{-polarized radiation,} \tag{1}$$

$$\theta_{0S} \simeq \arcsin[1 - (l\lambda/d)^2]^{1/2}, \quad S\text{-polarized radiation,} \tag{2}$$

where λ is the wavelength of the radiation, d is the period, and l is the index of the Fourier harmonic of the relief. These anomalies are observed only if the electric vector **E** is perpendicular to the lines of the grating. We will refer to this case as "resonant polarization." The angular distribution of the resonant absorption is determined by a convolution of the Wood's resonance of the grating, the angular distribution of the radiation, and its frequency spectrum.[2,3,5,6] The width and magnitude of the Wood's resonance of the grating are determined by optical and geometric characteristics of the relief.

In the present experiments we used metal diffraction gratings on which we had previously observed[5,6] some narrow (to 10′) and efficient (up to 100%) absorption

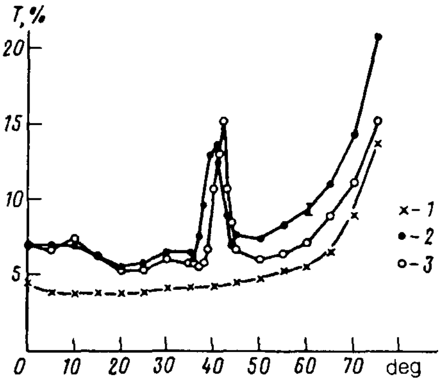

FIG. 1. Angular distribution of the spectral emissivity ($\lambda=5$ μm). *1*—Aluminum mirror; *2*—copper diffraction grating, for resonant *P*-polarized radiation and for a width b = 1.5 mm of the monochromator entrance slit; *3*—the same, but for $b=1$ mm.

peaks near the wavelength $\lambda=10.6$ μm. The test grating was placed in a special furnace on a rotatable stage. The temperature to which the test sample was heated was varied from 200 to 400 °C and was monitored with a Chromel–Alumel thermocouple. The error in the measurement of the angular position of the stage was no worse than 20′.

A converging lens with a focal length $f=9$ cm was placed at a point 50 cm away from the grating. The entrance slit of an SPM2 monochromator was positioned in the focal plane of this lens. With the help of this lens and of this slit, we selected an angular interval $\Delta\varphi=b/f$, where b is the width of the entrance slit of the monochromator, from the angular distribution of the emission from the heated region. In addition, a narrow band $\Delta\lambda=bs$ near $\lambda=5.0$ μm, where s is a characteristic of the monochromator prism, was selected from the frequency spectrum of the emission from the test sample by means of the monochromator. By varying the width of the entrance slit of the monochromator we were able to vary the widths of the angular interval and frequency band detected. We did not select the polarization of the radiation in these experiments.

An image of the exit slit of the monochromator was focused onto the sensitive area of an FSG-223A2 photoresistor in a nitrogen cryostat. The radiation from the test sample was modulated by a mechanical chopper in front of the entrance slit of the monochromator. The modulated signal from the photodetector was fed to the input of a lock-in detector with a time constant $\tau=7$ s. The readings of this detector were proportional to the power of the radiation emitted by the heated test sample in the narrow angular and spectral intervals at the wavelength $\lambda=5.0$ μm. An absolute calibration of the emissivity of the samples was carried out on the basis of the emission from graphite under the assumption that the emissivity of the latter at the wavelength $\lambda=5.0$ μm was[7] 50%. A lower limit was set on the emission power which could be measured by the noise of the photoresistor. The same noise determined the relative error of the measurements of the emissivity of the samples.

The operation of the apparatus was checked by measuring the angular distribution of the emissivity T of an aluminum mirror. The experimental results are shown by curve 1 in Fig. 1. We see that the experimental data correspond to the

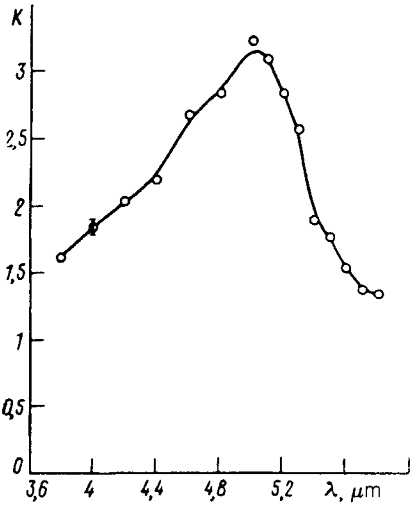

FIG. 2. Spectrum of the ratio (K) of emission coefficients of a copper grating and an aluminum mirror at the resonant angle $\theta_{0P}^{\exp}(l=1)=40.5°$.

Fresnel radiation from a smooth metal surface with S and P polarizations in the radiation.[2,3,5-7]

Figure 1 shows the angular distribution of the emissivity of a copper grating with a period $d=12.1$ μm and a groove depth $h=0.22$ μm for the resonant P polarization of the radiation (curves 2 and 3). We see here that under conditions such that the Wood's anomalies are observed for radiation with the P polarization [see Eq. (1)] we observe a peak in the emission: $\theta_{0P}^{\text{theor}}(l=1)=36°$, $\theta_{0P}^{\exp}(l=1)=40.5°$. The angular width of this peak at half-maximum is 4°, in agreement with a calculation incorporating the width of the angular interval ($\Delta\varphi\simeq 1°$) and the width of the frequency band ($\Delta\lambda\simeq 0.45$ μm) of the radiation being detected.[2,3,5,6] When the entrance slit of the monochromator was narrowed from $b=1.5$ mm (curve 2) to $b=1$ mm (curve 3), so that the angular and frequency widths of the detected radiation were reduced, we found that the observed emission peak became narrower and higher. This peak is thus determined by a convolution of the Wood's resonance in the emission of the grating, the angular interval of the radiation detected, and the frequency band of this radiation. Unfortunately, the measurement system was not sensitive enough to determine the amplitude and angular width of the Wood's resonance in the emission of the grating. When the entrance slit of the monochromator was narrowed further, the signal disappeared against the background of the photoresistor noise. We should point out that, if the conditions for the manifestation of Wood's anomalies are not satisfied, the emissivity of the grating is the Fresnel emissivity.

Obviously, Wood's anomalies should be seen in not only the angular distribution but also the spectrum of the thermal radiation of the grating. Figure 2 shows the wavelength dependence of the ratio (K) of the emissivities of a copper grating and an aluminum mirror at the resonant angle $\theta_{0P}^{\exp}(l=1)=40.5°$. We see that this plot also has a peak associated with the manifestation of a Wood's anomaly.

Figure 3 shows the angular distribution of the emissivity of a gold-plated grating

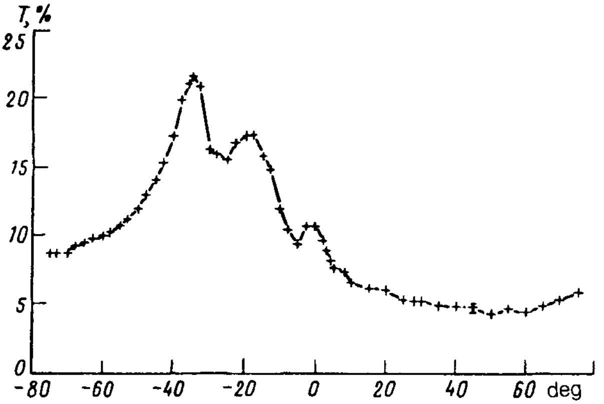

FIG. 3. Angular distribution of the spectral emissivity ($\lambda = 5\ \mu$m) of a gold-plated diffraction grating with a blaze angle for resonant P-polarized radiation.

with a period $d = 10.0\ \mu$m, a relief depth $h = 4.7\ \mu$m, and a blaze angle of about 35° for the case of the resonant P polarization of the radiation. We see that the asymmetry of the relief leads to an asymmetry in the angular distribution of the emissivity with respect to the normal to the surface. The same result has been seen[6] in studies of the absorption coefficient of such gratings. On the angular distribution of the emissivity we observe peaks in the emission under conditions corresponding to Wood's anomalies of orders $l = 1$ and $l = -3$: $\theta_{0P}^{\text{theor}}(l=1) = 30°$, $\theta_{0P}^{\text{exp}}(l=1) = 35°$, $\theta_{0P}^{\text{theor}}(l=-3) = 30°$, and $\theta_{0P}^{\text{exp}}(l=-3) = 20°$. As in the case of the copper grating, there is some discrepancy between the experimental and theoretical resonant angles. This difference is explained on the basis that Eqs. (1) and (2) are approximate, ignoring the finite values of the optical constants and the shape of the surface relief. When the finite values of the optical constants and the geometric parameters of the relief are taken into account, we find a shift of the resonant angle; this shift increases with increasing relief depth.[2,3]

The large angular width of the emission peaks of the gold grating is evidence that these peaks are due to a Wood's resonance in the emission from the grating, and that this large width is due to the large depth of the relief, which is comparable to the wavelength.[3,6]

In summary, we have observed some peaks in the emissivity of metal diffraction gratings which are a manifestation of Wood's anomalies. The height of the peaks observed here is essentially twice the background. However, the limiting height which these peaks might reach has not yet been studied definitively, either theoretically or experimentally.

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Translated by D. Parsons