

A new method for increasing the laser damage threshold of metal mirrors

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Abstract

In order to increase the damage threshold of metal mirrors we propose to create a special structure on the surface of the mirrors (“photonic surface”). This structure must have the period about $\lambda/2$ and will suppress propagation of surface plasmons with the frequency $\omega_0 = 2\pi c/\lambda$ along the surface. This structure will also slightly increase the heat removal from the mirror’s surface by the excitation of the thermostimulated plasmon emission from the surface. The heat removal from the surface is estimated and possible implementation of this approach for use with CO₂-lasers ($\lambda = 10.6 \mu\text{m}$) and Nd-YAG-lasers ($\lambda = 1.06 \mu\text{m}$) is analyzed. © 2000 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Laser damage of metal mirrors is a serious problem in high-powered infrared laser technology. The damage of metal mirrors is often accompanied by the development of spontaneous, highly periodic surface structures or “ripples” [1]. These structures are reversible when the laser energy is below the damage threshold and becomes permanent at high laser energy [2].

The processes of ripple formation show the important role of surface plasmons (SPs) in the laser damage of metal mirrors. The SP is a fundamental electromagnetic excitation mode of a metal–dielectric interface [3]. According to present understanding, the surface ripples appear due to interference of incident laser beams and SPs caused by random initial disturbances in the surface properties of the illuminated surface. These transverse variations may be separated analytically into individual spatial frequency components or sinusoidal surface grating along the surface. Incident

laser beams can excite the traveling SPs through appropriate spatial frequency components of surface imperfections, and interference between the incident beam and the surface wave, lead to spatially varying the total light intensity with the same period as its appropriate spatial frequency component of the surface imperfections. This intensity variation produces a growth rate for the surface imperfections, increasing the amplitude of its relevant spatial component of the surface variation, which will lead to increased coupling from the laser beam into the surface wave and so on.

The propagation directions of the SPs and, therefore, the orientation of the ripples, is determined by the polarization of the incident laser beam.

In recent years, the optical properties of materials that possess a periodic modulation of their refraction index on the scale of the wavelength of light have received much attention [4]. Such materials can exhibit photonic bandgaps that are much like the electronic bandgaps for electron waves traveling in the periodic potential of the crystal. In both cases, frequency intervals exist where wave propagation is forbidden. Materials where bandgaps take place for the propagation of bulk light waves are called “photonic crystals”. Sur-

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faces that produce such a bandgap for propagation of SP waves are called “photonic surfaces” [5]. For a single corrugation of the surface, the plasmon bandgap will extend only over a limited propagation range, but for more than one simple corrugation of the surface, the suppression of SP propagation in all possible directions is possible [5,7]. Barnes et al. have used the photonic surface to block a decay channel of molecular fluorescence into SP modes near a metal surface [6].

In this paper, we examine the possible uses of the photonic surface for increasing the damage threshold of metal mirrors. A photonic surface on a metal mirror will suppress the propagation of SPs caused by surface imperfections and will slightly increase the heat removal from the surface through thermostimulated plasmon emission.

2. Photonic bandgap for SPs caused by surface imperfections

At first we consider a single corrugation of the surface with the Bragg vector g and a pitch Λ , such that

$$g = 2k_{SP}$$

$$\Lambda = \frac{\lambda_{SP}}{2}. \quad (1)$$

The SP wavevector k_{SP} is [3]

$$k_{SP} = k_0 \left(\frac{\varepsilon_M}{\varepsilon_M + 1} \right)^{1/2}, \quad (2)$$

where $k_0 = \omega_0/c$ is the wavevector of the incident radiation and ε_M the dielectric constant of the metal at the given light frequency.

For SPs with $k_{SP} \parallel g$, Bragg scattering on the grating

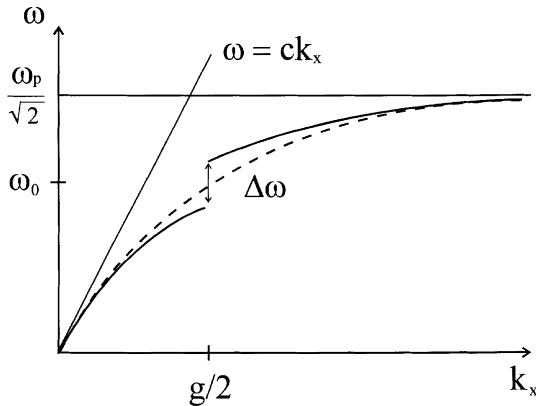


Fig. 1. SP dispersion curve for the flat surface (dashed line) and for the corrugated surface with the pitch $\Lambda = \lambda_{SP}/2$ (solid line).

takes place. The two counter-propagating SP modes set up a standing wave and, owing to the different surface charges and field distributions on the grating surface, associated with the two standing-wave solutions, a bandgap in the dispersion of the mode opens up [8]. The presence of a gap in the dispersion relation of SP propagating along a periodic surface has been known for a long time [9]. In Fig. 1, one can see the SP dispersion curve for a flat surface (dashed line) and for the corrugated surface with $\Lambda = \lambda_{SP}/2$ (solid line).

The bandgap width $\Delta\omega$ for small corrugation amplitude h ($h < \Lambda$) is [8,9]

$$\frac{\Delta\omega}{\omega_0} = \frac{2\pi h}{\Lambda \sqrt{|\varepsilon_M|}} = \frac{4\pi h}{\lambda \sqrt{|\varepsilon_M|}}. \quad (3)$$

A plasmon bandgap occurs not only for SPs propagating in the direction normal to the corrugation grooves, but also for SPs propagating in the direction range $-\psi < 0 < \psi$, where the angle ψ is [5]

$$\psi \simeq \arccos\left(\frac{2 - \Delta\omega/\omega_0}{2 + \Delta\omega/\omega_0}\right). \quad (4)$$

To achieve a total suppression for the SPs propagation across the surface in all possible directions, more than one set of corrugations is required. For hexagonal arrangement of a photonic surface, that is, for three gratings at 60° , ψ must be $\geq 30^\circ$, and consequently, $\Delta\omega/\omega_0$ must be ≥ 0.14 . Such values may be achieved in visible and near-infrared regions and not be practicable for $\lambda \sim 10.6 \mu\text{m}$.

For numeric estimations, we will use the data for two wavelength regions: $\lambda = 10.6 \mu\text{m}$ (CO_2 -lasers) and $\lambda = 1.06 \mu\text{m}$ (Nd-YAG-lasers). The reasons for the choice of these two regions are as follows: the reflection of the metal mirror with refraction index $\eta = n + i\kappa$ for normal incident is

$$R = \frac{(n-1)^2 + \kappa^2}{(n+1)^2 + \kappa^2}. \quad (5)$$

One can see that the employment of metals as very high reflection mirrors are possible when $n \gg 1$; $\kappa \gg 1$, and when $n \ll 1$; $\kappa \gg 1$. The former case is realized in the middle and far infrared regions ($n_{\text{Au,Ag,Cu}} \geq 12$; $\kappa_{\text{Au,Ag,Cu}} \geq 70$, for $\lambda \geq 10.6 \mu\text{m}$ [10]), and the later case is realized in the visible and near infrared regions for gold and silver ($n_{\text{Ag}} \leq 0.05$; $\kappa_{\text{Ag}} \sim 5$, $n_{\text{Au}} \leq 0.2$; $\kappa_{\text{Au}} \sim 4$, for $\lambda \simeq 0.63$ and $1.06 \mu\text{m}$ [11]).

So for $\lambda = 1.06 \mu\text{m}$, where $\varepsilon_{\text{Ag}} \simeq -60 + 0.6i$ ($\varepsilon_{\text{Au}} \simeq -51 + 3.9i$), the bandgap $\Delta\omega$ reaches the required value of 14% of the central frequency ω_0 at $h/\lambda \simeq 0.09(0.08)$ and full photonic surface creation for this wavelength seems quite possible.

But for $\lambda = 10.6 \mu\text{m}$ ($\varepsilon_{\text{Au, Ag, Cu}} \approx -5000 + 2000i$), the bandgap $\Delta\omega$ reaches the required value of 14% at

$h/\lambda \sim 1$, according to Eq. (3). This means that the approximation of small corrugation amplitude is broken-down and we cannot use Eq. (3).

If, for $\lambda = 10.6 \mu\text{m}$, we use a single corrugation with a reasonable amplitude $h \simeq 1 \mu\text{m}$ ($h/\lambda \simeq 1/10$), the bandgap $\Delta\omega/\omega_0$ will be about 0.017 and the maximum range of ψ will be only $\simeq \pm 10.57^\circ$. But the suppression of the SP propagation, even in such a narrow range, may be very useful for *linear* polarized laser radiation at a colinear corrugation and polarization orientation (the grating vector $\mathbf{g}$ must be parallel to the E field direction in the surface plane).

It is well known that the propagation direction of SPs, and the orientation of the grating vectors $\mathbf{g}_{\text{ripples}}$ of the formed ripples, are confined to a narrow range of angles very accurately parallel to the E field direction (and only for a very high-intensity condition, for single-shot macroscopic damage of the surface, the $\mathbf{g}_{\text{ripples}}$ directions distributed over 5 or 10° about the E field direction) [1].

So even such a narrow bandgap ($\Delta\omega/\omega_0 \simeq 0.017$) in one direction of the SPs propagation may increase the damage threshold of metal mirrors, and therefore this approach may be used even for $10.6 \mu\text{m}$ radiation.

In the rest of this section, we compare the bandgap width, $\Delta\omega/\omega_0$ with the width of the plasmon curve, $\delta\omega/\omega_0$, which arises due to SP dissipative damping. The ratio $\Delta\omega/\delta\omega$ may be used for a quantitative estimation of the decreasing of the SP intensity on the “photonic surface”. The width $\delta\omega$ may be estimated as

$$\delta\omega/\omega_0 = \frac{\text{Im}\left(\sqrt{\frac{\varepsilon_M}{\varepsilon_M + 1}}\right)}{\text{Re}\left(\sqrt{\frac{\varepsilon_M}{\varepsilon_M + 1}}\right)}, \quad (6)$$

where $\text{Re}()$ and $\text{Im}()$ are real and imaginary parts of the function, respectively. Expanding $\varepsilon_M = \varepsilon' + i\varepsilon''$, and assuming that $|\varepsilon''| \ll |\varepsilon'|$, one can obtain [3]:

$$\begin{aligned} \text{Re}\left(\sqrt{\frac{\varepsilon_M}{\varepsilon_M + 1}}\right) &= \left(\frac{\varepsilon'}{\varepsilon' + 1}\right)^{1/2} \\ \text{Im}\left(\sqrt{\frac{\varepsilon_M}{\varepsilon_M + 1}}\right) &= \frac{\varepsilon''}{2\varepsilon'^2} \left(\frac{\varepsilon'}{\varepsilon' + 1}\right)^{3/2}, \end{aligned} \quad (7)$$

and

$$\delta\omega/\omega_0 = \frac{\varepsilon''}{2\varepsilon'(\varepsilon' + 1)}. \quad (8)$$

Therefore, using the previously given values of ε'_{Ag} and $\varepsilon''_{\text{Ag}}$, $\delta\omega/\omega_0 \simeq 4 \times 10^{-5}$ and $\Delta\omega/\delta\omega \simeq 430$ for

$\lambda = 10.6 \mu\text{m}$; and $\delta\omega/\omega_0 \simeq 8.5 \times 10^{-5}$ and $\Delta\omega/\delta\omega \simeq 1900$ for $\lambda = 1.06 \mu\text{m}$ (we have taken $\Delta\omega$ at $h/\lambda = 1/10$).

3. Heat removal from the mirror through emission of thermostimulated plasmons

The incident laser radiation will not “see” the existence of the grating on the photonic surface, because the grating pitch $\Lambda < \lambda/2$ (for normal incidence an even weaker condition $\Lambda < \lambda$ is sufficient). But this surface structure will act as a common diffraction grating for thermostimulated surface plasmons (TSPs) with $\lambda_{\text{TSP}} > 2\Lambda$.

TSP is the SP excited by the heat energy of the body (see [12] and references therein). The TSP is also (like an SP), a nonradiative electromagnetic mode on the *flat* surface. On the *corrugated* surface, part of the energy of the TSP will be extracted into a vacuum above the surface.

When the temperature of the grating is equal to the temperature of the environment, the TSPs emit and absorb equal amounts of the energy. But when the temperature of the grating is increased (due to absorption of a part of the laser radiation), heat removal from the grating through TSP emission takes places.

In the Appendix we derive that the radiative heat removal from the flat mirror may be estimated as:

$$\begin{aligned} P_{\text{M}}^{\text{flat}}(T) &\simeq \sigma T^4 \frac{\gamma}{\omega_p} S \left[\frac{8}{3} - 360 \frac{\zeta(5)}{\pi^3} \frac{kT}{\hbar \omega_p} + \frac{64}{21} \pi^2 \left(\frac{kT}{\hbar \omega_p} \right)^2 \right. \\ &\quad \left. + \frac{\gamma}{\omega_p} \left(\frac{25}{6} - 2C - 2 \ln \left(\frac{\hbar \omega_p}{kT} \right) + 180 \frac{\zeta'(4)}{\pi^4} \right) \right], \end{aligned} \quad (9)$$

where σ is the Stefan–Boltzmann constant, ω_p is the plasma frequency of electrons, $\gamma = \gamma_{293}(1 + \alpha(T - 293))$,

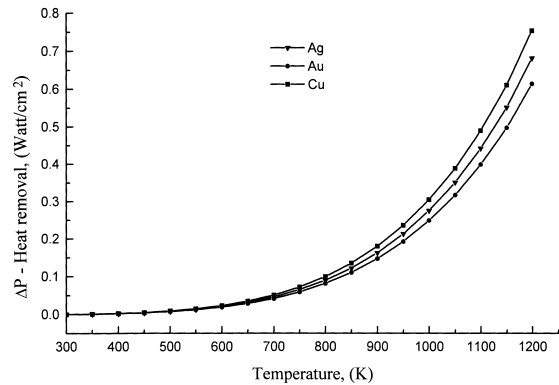


Fig. 2. Radiative heat removal from the flat mirror $\Delta P(T) = P_{\text{M}}^{\text{flat}}(T) - P_{\text{M}}^{\text{flat}}(300 \text{ K})$.

γ_{293} is the collision frequency of electrons at 293 K, α is the temperature coefficient of the electrical impedance of the material, S is the area of the mirror, $C \simeq 0.577$ is the Euler's constant and $\zeta(Z)$ is the Riemann Zeta function ($\zeta(5) \simeq 1.037$ and $\zeta'(4) \simeq -0.069$).

The heat removal from the flat mirror placed inside an environment with the temperature 300 K $\Delta P(T) = P_M^{\text{flat}}(T) - P_M^{\text{flat}}(300 \text{ K})$ is presented in Fig. 2.

For a mirror with one-dimensional corrugation (common diffraction grating), we have not derived the analytical approximation for heat removal, and will use numerical computation to estimate the heat removal from the grating (see the Appendix for details). The results of the computation for radiation with $\lambda \sim 10.6 \mu\text{m}$ is shown in Fig. 3. We take the silver, gold and copper gratings with the pitch $\Lambda = 5.3 \mu\text{m}$, and corrugation amplitude $h = \lambda/10 \simeq 1 \mu\text{m}$.

One can see that the extra radiative heat removal from the grating in respect to the radiative heat removal from the flat surface is not very large (several percent). The physical reason is that an angular dependence of the TSP emission at the given light frequency has a very narrow width when corrugation amplitude of the grating is small ($\delta\theta$ [in radians] $\sim \delta\omega/\omega_0$). If corrugation amplitude of the grating increases, then starting with some point, the angular width of the SP resonance increases as well, but an amplitude of the SP resonance decreases so that an appropriate integral taken by the angle θ remains the same. The dependence of the heat removal respective to the corrugation amplitude of the gold grating at 700 K is shown in Fig. 4.

We carry out our calculations for one-dimensional grating. For a hexagonal arrangement of the corrugations (three gratings at 60°), one may expect an increase of the heat removal by a factor of approximately three.

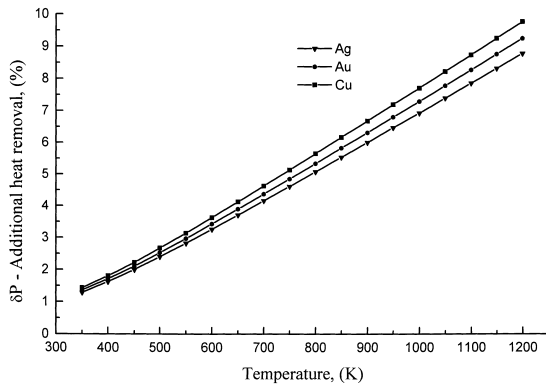


Fig. 3. Increase of the radiative heat removal from the grating with $h = \lambda/10$, in the ratio to the radiative heat removal from the flat mirror ($h = 0$).

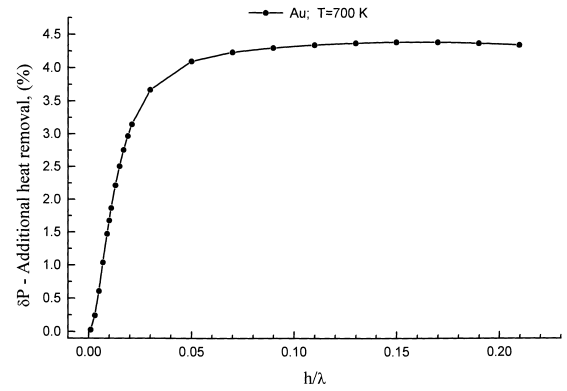


Fig. 4. The dependence of the heat removal, respective to corrugation amplitude of the gold grating at 700 K.

4. Conclusions

In this paper we have proposed the use of a “photonic surface” to increase the damage threshold of metal mirrors. The SPs propagation is forbidden on such a surface. Inasmuch as the SP wave is strongly localized at the interface and its intensity is very large just above the surface, the elimination of the SPs caused by the surface imperfections must be very useful for increasing the damage threshold.

Moreover, the photonic surface will slightly increase the heat removal immediately from the interface.

The calculations of the frequency bandgaps, forbidden direction ranges and radiative heat removal from the flat and corrugated surface are performed for Ag, Au and Cu.

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Appendix A

Let us start with the estimation of the heat removal from the flat metal mirror with permittivity given by the Drude's model:

$$\epsilon_M = \epsilon' + i\epsilon'' = 1 - \frac{\omega_p^2}{\omega^2 + i\gamma\omega}$$

$$\epsilon' = 1 - \frac{\omega_p^2}{\omega^2 + \gamma^2} \simeq -\frac{\omega_p^2}{\omega^2 + \gamma^2}$$

$$\varepsilon'' = \frac{\gamma \omega_p^2}{\omega(\omega^2 + \gamma^2)}, \quad (1')$$

where ω_p and γ are the plasma frequency and collision frequency of electrons.

We will use the Leontovich approximation (see, for example, [13]) for our computations. In this approximation the Frenel's equations have the form:

$$r_s = \frac{E_s}{E_s^0} = -\frac{1 - z \cos(\theta)}{1 + z \cos(\theta)}$$

$$r_p = \frac{E_p}{E_p^0} = -\frac{\cos(\theta) - z}{\cos(\theta) + z}, \quad (2')$$

where $z = z' + iz'' = 1/\sqrt{\varepsilon_M}$ is the surface impedance of the metal.

Therefore,

$$R_s = r_s r_s^* = \frac{(z' \cos(\theta) - 1)^2 + z''^2 \cos^2(\theta)}{(z' \cos(\theta) + 1)^2 + z''^2 \cos^2(\theta)}$$

$$R_p = r_p r_p^* = \frac{(\cos(\theta) - z')^2 + z''^2}{(\cos(\theta) + z')^2 + z''^2}, \quad (3')$$

where real and imaginary parts of the z are:

$$z' = \frac{1}{\sqrt{2}} \frac{\sqrt{\varepsilon'^2 + \varepsilon''^2} + \varepsilon'}{\sqrt{\varepsilon'^2 + \varepsilon''^2}}$$

$$z'' = -\frac{1}{\sqrt{2}} \frac{\sqrt{\varepsilon'^2 + \varepsilon''^2} - \varepsilon'}{\sqrt{\varepsilon'^2 + \varepsilon''^2}}. \quad (4')$$

To estimate the amount of the heat energy emitted from the surface, we will use Kirchoff's law:

$$P_M(\theta, \varphi, \omega, T) = (1 - R(\theta, \varphi, \omega)) P_{\text{black}}(\omega, T), \quad (5')$$

where R is the reflectivity of the mirror, θ is the incident angle of the plane wave with the frequency ω , φ is the angle between the plane of incidence and the Bragg vector $\mathbf{g}$ ($\mathbf{g}$ is absent in the case of the flat surface), P_{black} is the spectral radiation intensity of the black body with the temperature T , given by Plank's law:

$$P_{\text{black}}(\omega, T) = \frac{\hbar \omega^3}{4\pi^3 c^2 (\exp(\hbar \omega / kT) - 1)}. \quad (6')$$

The total heat removal from the surface is:

$$P_M(T) = \int_0^\infty \left[\int_0^{\pi/2} \left[\int_0^{2\pi} A(\theta, \varphi, \omega) d\varphi \right] \right. \\ \left. \times \sin(\theta) \cos(\theta) d\theta \right] P_{\text{black}}(\omega, T) d\omega, \quad (7')$$

where

$$A(\theta, \varphi, \omega) = \frac{1}{2} (A_s(\theta, \varphi, \omega) + A_p(\theta, \varphi, \omega)) = 1 - \frac{1}{2} (R_p(\theta, \varphi, \omega) + R_s(\theta, \varphi, \omega)) \quad (8')$$

is the isotropic absorption coefficient at a given direction and frequency.

The integrated absorptions for s- and p-polarizations are:

$$\frac{A_s(\omega)}{2\pi} = \frac{1}{2} - \int_0^{\pi/2} R_s \sin(\theta) \cos(\theta) d\theta \\ = \frac{1}{2} - \frac{1}{2(z'^2 + z''^2)^2 z''} \\ \times \left[-8z' \left(z''^3 - z''^2 \arctan\left(\frac{z''}{1+z'}\right) \right) \right. \\ \left. + 2z'^2 (z''^3 + 4z'' \ln((1+z')^2 + z''^2)) \right. \\ \left. - 8z'^3 \left(z'' + \arctan\left(\frac{z''}{1+z'}\right) \right) + z'^4 z'' + z''^5 \right]$$

$$\frac{A_p(\omega)}{2\pi} = \frac{1}{2} - \int_0^{\pi/2} R_p \sin(\theta) \cos(\theta) d\theta \\ = -4z' \left(z'' \arctan\left(\frac{z''}{z''^2 + z' + z'^2}\right) - 1 \right) \\ - 4z'^2 \ln\left(\frac{(1+z')^2 + z''^2}{z'^2 + z''^2}\right) \\ + 4\frac{z'^3}{z''} \arctan\left(\frac{z''}{z''^2 + z' + z'^2}\right). \quad (9')$$

The frequency dependence of the z' and z'' may be found from (4') and (1'):

$$z' = \frac{1}{\sqrt{2}} \sqrt{\frac{\omega^4}{\omega_p^4} + \frac{\omega^2 \gamma^2}{\omega_p^4} - \frac{\omega^2}{\omega_p^2}}$$

$$z'' = -\frac{1}{\sqrt{2}} \sqrt{\frac{\omega^4}{\omega_p^4} + \frac{\omega^2 \gamma^2}{\omega_p^4} + \frac{\omega^2}{\omega_p^2}}. \quad (10')$$

Expanding Eqs. (10') in a Taylor series, with respect to the small parameter γ/ω_p , one can find the approximation:

$$z' \simeq \frac{1}{2} \frac{\gamma}{\omega_p} - \frac{1}{16} \frac{\gamma^3}{\omega^2 \omega_p}$$

$$z'' \simeq -\frac{\omega}{\omega_p} - \frac{1}{8} \frac{\gamma^2}{\omega \omega_p}. \quad (11')$$

To find the frequency dependence of the absorption, we substitute Eqs. (10') into Eqs. (9') and expand the result in the Taylor series of the small parameter γ/ω_p . Retaining the first and second terms, we have:

$$A(\omega) \simeq \frac{8}{3} \pi \frac{\gamma}{\omega_p} + \frac{1}{2} \pi \left(\frac{\gamma}{\omega_p} \right)^2 - 2\pi \left(\frac{\gamma}{\omega_p} \right)^2 \ln \left(\frac{\omega_p}{\omega} \right) - \pi^2 \frac{\gamma \omega}{\omega_p^2} + \frac{8}{5} \pi \frac{\gamma \omega^2}{\omega_p^3}. \quad (12')$$

Performing the last integration in Eq. (7'), we obtain the result:

$$P_M^{\text{flat}}(T) \simeq \sigma T^4 \frac{\gamma}{\omega_p} S \left[\frac{8}{3} - 360 \frac{\zeta(5)}{\pi^3} \frac{kT}{h \omega_p} + \frac{64}{21} \pi^2 \left(\frac{kT}{h \omega_p} \right)^2 + \frac{\gamma}{\omega_p} \left(\frac{25}{6} - 2C - 2 \ln \left(\frac{h \omega_p}{kT} \right) + 180 \frac{\zeta'(4)}{\pi^4} \right) \right], \quad (13')$$

where $\sigma = \pi^2 k^4 / (60 c^2 h^3)$ is the Stefan–Boltzmann constant, $\gamma = \gamma_{293}(1 + \alpha(T - 293))$, γ_{293} is the collision frequency of electrons at 293 K, α is the temperature coefficient of the electrical impedance of the material, S is the area of the mirror, $C \simeq 0.577$ is the Euler's constant and $\zeta(Z)$ is the Riemann Zeta function ($\zeta(5) \simeq 1.037$ and $\zeta'(4) \simeq -0.069$). We have taken into account the temperature dependence of γ , using the fact that $\gamma \sim \varrho$ [10], where ϱ is the electrical impedance of the metal. Approximation (13') is true for $h\gamma/(2.82k) \ll T \ll h\omega_p/(2.82k)$ (e.g. for Ag: $189 \text{ K} \ll T \ll 3.8 \times 10^4 \text{ K}$). For a rough estimation, (13') may be taken in the form:

$$P_M^{\text{flat}}(T) \approx \frac{8}{3} \sigma T^4 S \frac{\gamma_{293}(1 + \alpha(T - 293))}{\omega_p}. \quad (14')$$

To calculate the heat removal from the *corrugated* surface (from the diffraction grating), we repeat our computation performing the numerical integration of Eq. (7'). The reflection from the grating may be found from the next equations [14]:

$$E_s = r_s \left[E_s^0 - 2i\omega \frac{|a_s|^2 E_s^0 + a_s^* a_p E_p^0}{F} \right] \\ E_p = r_p \left[E_p^0 - 2i\omega \frac{|a_p|^2 E_p^0 + a_p^* a_s E_s^0}{F} \right], \quad (15')$$

where

$$a_s = \left(\frac{|z| \omega \cos(\theta)}{2} \right)^{1/2} h g \frac{\sin(\varphi)}{1 + z \cos(\theta)},$$

$$a_p = \left(\frac{|z| \omega \cos(\theta)}{2} \right)^{1/2} h g \frac{\cos(\varphi)}{\cos(\theta) + z},$$

$$F = \omega^2 - \omega_{sp\pm}^2 + i\omega(\gamma_d + \gamma_r),$$

$$\omega_{sp\pm} = (\omega^2 \sin^2(\theta) + g^2 c^2 \mp 2\omega g c \sin(\theta) \cos(\varphi))^{1/2} (1 - |z|^2/2),$$

$$\gamma_d = -\omega \text{Im}(z^2),$$

$$\gamma_r = |a_s|^2 + |a_p|^2. \quad (16')$$

Here, γ_r is the constant of the radiative damping of the SP, and γ_d is the constant of the dissipative damping of the SP [$\gamma_d \simeq 2\delta\omega$ from Eq. (8)].

The first term in the square bracket of Eqs. (15') describes the reflection from the flat surface (nonresonant term). r_s and r_p are given by Eqs. (2'). The second term in the square bracket describes the role of the SPs excitation in the reflection from the grating with the Bragg vector g and the corrugation amplitude h . The results of the calculations for silver, gold and copper gratings are illustrated in Fig. 3. The following parameters are used:

Au:	$\gamma_{293} = 330 \text{ cm}^{-1},$	$\alpha = 0.00402 \text{ K}^{-1},$
	$\omega_p = 70,200 \text{ cm}^{-1};$	
Ag:	$\gamma_{293} = 370 \text{ cm}^{-1},$	$\alpha = 0.0043 \text{ K}^{-1},$
	$\omega_p = 74,500 \text{ cm}^{-1};$	
Cu:	$\gamma_{293} = 370 \text{ cm}^{-1},$	$\alpha = 0.00433 \text{ K}^{-1},$
	$\omega_p = 67,000 \text{ cm}^{-1}; \Lambda = 5.3 \text{ } \mu\text{m}, h = \lambda/10 \simeq 1 \text{ } \mu\text{m}.$	

Extra heat removal from the grating with respect to the heat removal from the flat surface $\delta P(T)$ we present in the form

$$\delta P(T) = \frac{\Delta P^{\lambda/10}(T) - \Delta P^0(T)}{\Delta P^0(T)} 100\%, \quad (17')$$

where $\Delta P^{\lambda/10}(T) = P_M^{\lambda/10}(T) - P_M^0(300 \text{ K})$ and $\Delta P^0(T) = P_M^0(T) - P_M^0(300 \text{ K})$ are the heat removal from the grating (with $h = \lambda/10$) and from the flat surface ($h = 0$) placed inside an environment at 300 K. The heat removal from the flat surface, given by Eqs. (9) and (13'), agrees well with the heat removal from the grating with $h = 0$ ($P_M^0(T)$), calculated by the numerical integration of Eq. (7').

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