# Wavelength-independent field enhancement in subwavelength gratings

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**Abstract**

We show that lamellar metal gratings exhibit total transmission of incident radiation and strong nonresonant electric field enhancement in extremely subwavelength regime (in the nanometer-sized slits). With high accuracy the enhancement equals the ratio of the grating period to the slit width, it is independent on the wavelength and metal thickness.

Aperture films and metallic gratings have a long story of investigations in optics with well-known applications as color selective filters, photodetectors, collimators, for surface enhanced raman scattering and fluorescence, detection of refractive index, etc. [1] Metallic nanostructures having micro to nanometer-sized constitutive elements also have potential in lower frequencies, and homogenizable metal-dielectric composites with negative or any other desired index of refraction is not the only option here. For example, recently it was shown that a nanometer-wide single slot in a thin gold film provides pronounce field enhancement at THz frequencies [2]. Metallic slabs featuring nanometer-sized perforation can be simultaneously used both at visible and THz parts of spectrum what opens new prospects for these structures to be used as fast all-optical components where electromagnetic wave in one frequency range acts as a control pulse governing information signal from the other part of spectrum.

Huge real and imaginary parts of metal permittivity at low frequencies make perfect electric conductor description of metal nearly ideal approximation. At THz frequencies negligible percent of radiation impinging on the metal penetrates inside because almost all incident radiation is reflected at the frontier between the dielectric and metal and the reflected wave has phase shift of $\pi$. Small portion of THz wave energy passed inside the metal decays spatially slow meaning low absorbance due to skin depth increased by several times at low frequencies compared to visible. Thus at THz frequencies a 20-100nm thick gold metallic film becomes non-transparent and reflects most of incident on it radiation whereas, for example, 20nm-film under visible illumination can tunnel up to 50 % of light. Metal is indispensable material for THz range in this sense because, for example, $VO_2$ films of the same thickness experience only on $20\%$ change in their transmission after dramatic change of refractive index from 1 to 10000 due to phase transition [3]. The ability of metal to effectively govern long-wavelength radiation on the length scale of nanometers with low absorption is of good use when we are interested in strong field concentration in air gaps in metals without scarifying good transmission.

In this paper we consider field enhancement in lamellar metallic gratings at a fundamental limit $\omega \to 0$ and investigate range of frequencies where electrostatic approximation solution can be applicable for propagating electromagnetic waves. The static model gives rule for electric field inside a slit as a ratio of grating period to the slit width, the enhancement being defined relatively to the amplitude of incident wave. It turns out that this rule can be satisfied quite generally for periodically perforated metal films

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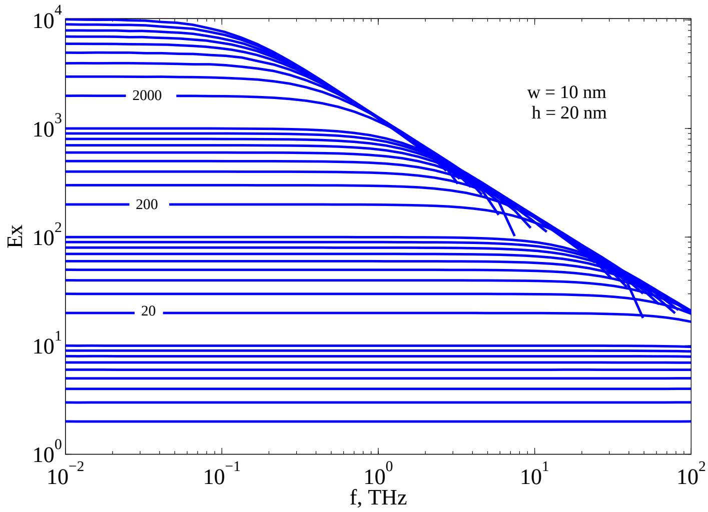


Fig. 1: Field enhancement in a 10nm-width slits cut in a 20nm-thick film versus the frequency for different grating periods $P$. The enhancements in quasistatic limit are chosen to be $E_x^s = (2 : 1 : 10) \cdot 10^n$ where $n$ changes from zero to three, the corresponding period of grating is $P = \text{w}\ E_x^s$.

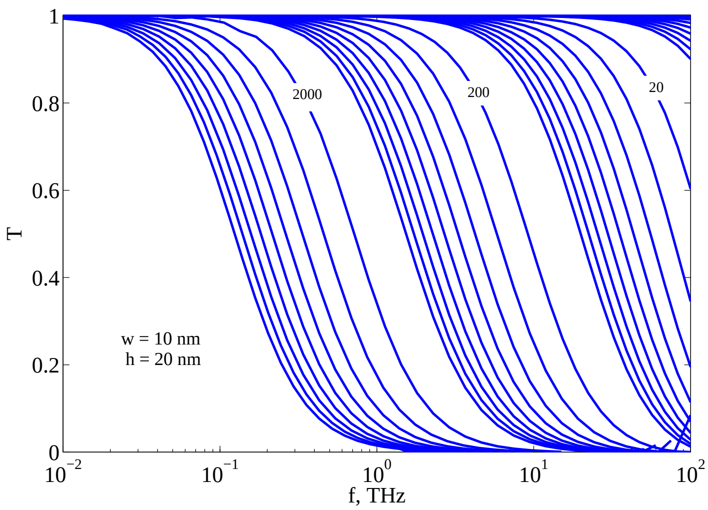


Fig. 2: Transmission of the same structure as in Fig. 1.

starting from zero up to THz frequencies unless the grating period or film thickness becomes close to the wavelength of light, e.g. we step in the regime where resonance effects appear. Fulfilment of the electrostatic solution for enhancement given by oscillating electromagnetic waves is closely connected with perfect symmetry of the field distribution on both sides of free-standing metal film what immediately means total energy transfer from upper to lower half-space and thus strictly unitary transmission not available in single apertures. Thus adding periodical openings to metal membrane drastically change its transmission from zero to one, what is naturally for utilizing in switching [3]. By doing numerical simulation we explore field enhancements up to $10^4$ in a 5nm air gap in periodic structures in 0-0.1THz range. The combination of controllable field concentration given by simple law together with unitary transmission both available simultaneously and in the broad range of frequencies paves the way for usage of metallic gratings for improvement of THz sources, detectors and sensors, as wavelength-independent polarizers and essentially for molecular absorption spectroscopy [4].

Assuming the unit amplitude of the incident field, we denote the enhancement factor as $E_x$ keeping in mind that the field is mainly directed across the slit (in $x$-direction). From Ref. [2] it is known that for the single slit the enhancement factor is proportional to the inverse frequency $1/f$. When we consider the periodic grating the situation dramatically changes. For large periods $P$ (like for the upper curve in Fig. 1 corresponding to 100 $\mu$m) we indeed see the dropping frequency dependence. But it is not the case for small periods, which are characterized by the wide THz plateau. This amazing effect implies that all the spectrum constituents of the THz pulse will be equally enhanced in the near field of the slit, while the single slit acts as the low-frequency filter. The range of frequency-independent field enhancement can be even broadened to the infrared, if the period of the grating is about tens of nanometers. The curves in Fig. 1 demonstrate the general principle of the flat field enhancement. To have very high enhancements, we considered very narrow slits and extremely long periods. Qualitatively the results of Fig. 1 keep for sub-skin-depth metal films and for any arbitrarily choice of slit width $w$ and period $P$ smaller than the wavelength of light.

The deviation of the enhancement factor $E_x$ from the wavelength-independent value can be analyzed using the transmission curves (see Fig. 2). As it has been mentioned before, the transmission is near the unity for the periodic metallic gratings in THz regime, if the period $P$ is small. So, the THz pulse can be strongly enhanced in near field (in the slits) and completely transmitted in the far field. For example, this holds for $E_x = 200$ and $f < 1$ THz. If $f > 1$ THz, the significant filtering of the signal occurs.

The results discussed above can be explained using the electrostatic approximation and microscopic Drude-Lorentz theory. The electrons of the metal film are affected by the force from the edges of the slit, which can be described by the analytical formula for the homogeneously charged strip in statics. The electrons make oscillations like in plasma. Determining the electron displacement and the charge at the slit edge we get the field at the center of the slit (enhancement factor). In the limit $P \gg w$ and $|\varepsilon^{(m)}| \gg 1$ we derive

$$E_x = \frac{2\omega_p^2 E^{(m)}}{\pi\omega_0^2} \arctan(h/w) = \frac{P}{w}\sqrt{\varepsilon'_m} E^{(m)} \approx \frac{P}{w}\frac{\sqrt{\varepsilon'_m(f)}}{\sqrt{\varepsilon_m(f)}} \frac{\mathrm{i}}{\sin(\pi f h\sqrt{\varepsilon_m(f)})} E^{(inc)}, \quad (1)$$

where $h$ and $\varepsilon'_m$ are the thickness and real part of the dielectric permittivity of the metal, $E^{(m)}$ is the electric field in metal (homogeneous for a sub-skin-depth film), $E^{(inc)}$ is the incident electric field, $\omega_0$ is the electron resonance frequency (function of the geometrical parameters), $\omega_p$ is the plasma frequency. Such an enhancement factor $E_x$ indeed depends on the geometrical parameters as $P/w$. It should be noted that $E_x$ calculated as Eq. (1) is frequency independent in THz range with good accuracy. In the limit of extremely thin metal film we can regard electrons in vacuum illuminated just by the incident field, so that $\varepsilon_m = 1$ and $E^{(m)} = E^{(inc)} = 1$. Then we directly arrive at the equation $E_x = (P/w)\sqrt{\varepsilon'_m} E^{(m)} = P/w$.

In conclusion, we have revealed the wavelength-independent enhancement factor and total transmission for the metallic gratings in THz regime. We have performed the numerical and analytical modeling of the near-field enhancement in the slits. The discussed phenomena can find applications in THz spectroscopy and effective control of light.

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