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Surface plasmon polaritons in metallo-dielectric meander-type gratings

A. B. Akimov[+1)], *A. S. Vengurlekar*[*], *T. Weiss*[∇□], *N. A. Gippius*[+□], *S. G. Tikhodeev*[+]

[+]*A.M. Prokhorov General Physics Institute RAS, 119991 Moscow, Russia*

[*]*Tata Institute of Fundamental Research, 400005 Mumbai, India*

[∇]*4th Physics Institute, University of Stuttgart, 70550 Stuttgart, Germany*

[□]*LASMEA, UMR 6602 CNRS, Université Blaise Pascal, 63177 Aubière, France*

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The optical properties of a gold film deposited on a quartz substrate with periodic grooves were investigated theoretically. The main peculiarities of the spectra are due to the excitation of the surface plasmon polaritons (SPPs). It is shown that the empty lattice approximation (ELA) for the SPPs is well applicable for the structure of interest. Two different approaches for deriving the air-gold SPP dispersion curves are compared. Our special attention is focused on the wavelength region approaching the d-band in gold, where the dielectric function is of a strongly non-Drude-type.

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Metallo-dielectric periodic structures have attracted great interest in recent years because of their potential applications in constructing composites with tailored optical properties (so-called metamaterials) [1 – 3]. The optical properties of these structures are due to both collective electron effects (localized and delocalized plasmons) and photonic resonances. Numerical modeling of metallic structures is often a difficult problem because of complicated frequency dependence of the dielectric permittivity of metals and slow convergence of common methods. However, if the structure is illuminated by a plane wave and the surface plasmon polariton (SPP) is excited, the periodicity itself allows some important conclusions.

The electric and magnetic fields in a periodic structure obey the Bloch's theorem, like the electron wavefunction in a crystal, and the zone scheme can be built for the dispersion curves of the SPPs. A zero order approximation is to neglect the real modulation of the structure and to fold the dispersion curves $\omega(k)$ of the SPPs for a perfectly flat interface into the first Brillouin zone. Here, ω denotes the SPP frequency and k is the SPP wave vector along the interface. This is called the empty lattice approximation (e.g., see Ref. [4]), in analogy to the free electron model of the solid state theory. It is very important that k should obviously be real due to the translational invariance of the structure. The values of k and the real part of ω allow to predict the positions of the anomalies in the optical spectra [5, 6], while the energy losses and, consequently, the line width of the resonances can be described in terms of the imaginary part of ω. If the translational invariance is absent, the way to draw the dispersion curves of the SPPs is, in opposite, to calculate complex k as a function of real frequency ω. Then Re $k(\omega)$ gives the SPP dispersion, and Im $k(\omega)$ is the inverse SPP propagation length. The difference is usually not large (e.g., for Ag or Au and wavelengths $\lambda > 550$ nm), but situations can be found where it is not negligible. In this paper we address this problem theoretically using the empty lattice approximation (ELA) and numerical studies.

The investigated structure is a so-called meander (Fig.1). It is characterized by deep grooves etched in

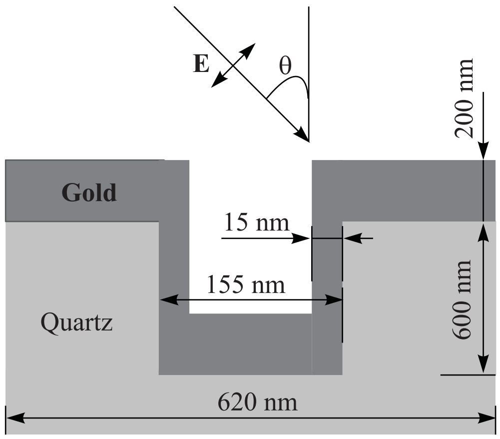

Fig.1. The geometry of the incident p-polarized light and the unit cell of the structure

quartz and a thick gold layer deposited on this substrate. Recent experiments [6] showed that the optical proper-

[1)]e-mail: toshaakimov@gmail.com

ties of meander-type modulated gold structures can be interpreted in terms of SPP excitation. The dispersion law of these surface electromagnetic waves on a flat interface of two infinite half spaces of air and metal is given by the well-known relation [7]

$$k^2 = \frac{\omega^2}{c^2}\frac{\varepsilon(\omega)}{\varepsilon(\omega)+1}, \tag{1}$$

where $\varepsilon(\omega)$ is the dielectric function of the metal (or its ratio to that of the outside dielectric surrounding if it is not air). The electric field of such waves decreases exponentially both into air and metal. Since the phase matching between exponential and propagating waves is impossible, one cannot excite a surface wave on a flat interface via direct light beam. However, spatial modulation of the metal layer breaks the conservation law of the wavevector along the interface and allows to excite the SPP. In this paper we concentrate on examining the reliability of the simplest dispersion law (1) for modulated structures in different wavelength ranges.

Since gold is an absorptive material and its dielectric function has a non-zero imaginary part, we cannot obtain simultaneously real values of ω and k solving Eq. (1). If the optical excitation is localized, or there are only isolated surface defects, we can take a real value for frequency ω, calculate a complex function $k(\omega)$ and then use its real part to explain the positions of the optical anomalies. In contrast, in case of periodic modulation we have to take a real value of k and find a complex $\omega(k)$ solving Eq. (1). For doing that, we have to make the analytical continuation of the dielectric function of gold to the complex frequency plane. An appropriate way for the latter is to use a reasonable analytical formula for $\varepsilon(\omega)$. Here we use the Lorentz-Drude model [8], which takes into account both the intraband and interband electronic transitions in gold:

$$\varepsilon(\omega) = 1 - \frac{f_0\omega_p^2}{\omega\,(\omega + i\gamma_0)} + \sum_{j=1}^{n}\frac{f_j\omega_p^2}{\omega_j^2 - \omega^2 - i\omega\gamma_j}. \tag{2}$$

Figure 2 compares the results of Eq. (2) with the values of f_j, ω_j, γ_j from [8] and the experimental data [9]. It is seen that the model describes the dielectric function $\varepsilon(\omega)$ correctly, in spite of its very complex behavior.

The SPP dispersion laws obtained via the Lorentz-Drude model are shown in Fig.3. It is important that there is a polaritonic-like gap in the SPP dispersion law if we assume k to be real, and there are lower polariton (LP) and upper polariton (UP) branches. It is not surprising at all, because each term in the sum in Eq. (2) formally coincides with the polaritonic susceptibility [10]. To estimate the lower Re $\hbar\omega_l$ and the upper

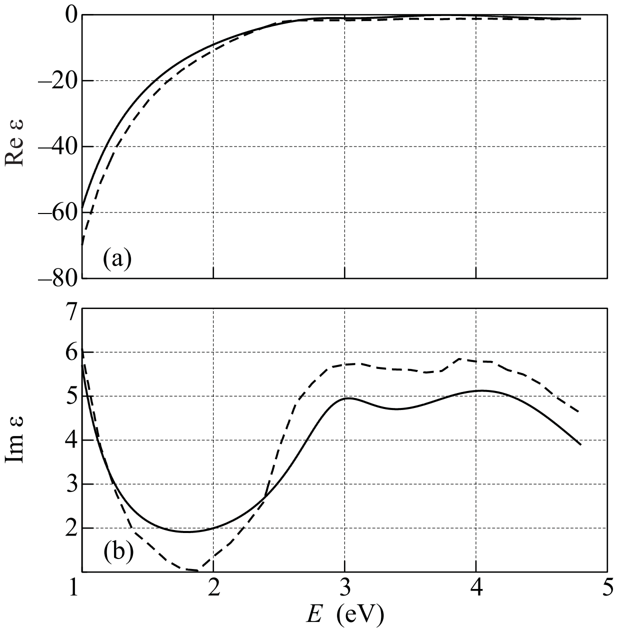

Fig.2. Real (a) and imaginary (b) parts of the dielectric function of gold. Solid lines: the Lorentz-Drude model. Dashed lines: the tabled data [9]

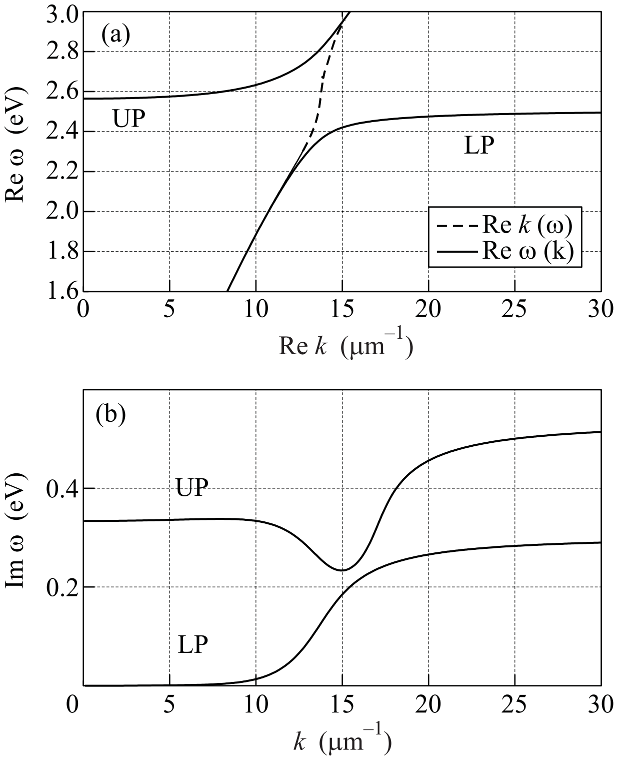

Fig.3. The air-gold SPP dispersion laws in the Lorentz-Drude model: (a) Comparison of two alternative approaches. (b) Imaginary part of the energy of the SPP

Re $\hbar\omega_u$ edges of the polaritonic gap we solve numerically the equations $\varepsilon(\omega_l) = -1$ and $\varepsilon(\omega_u) = 0$, respectively.

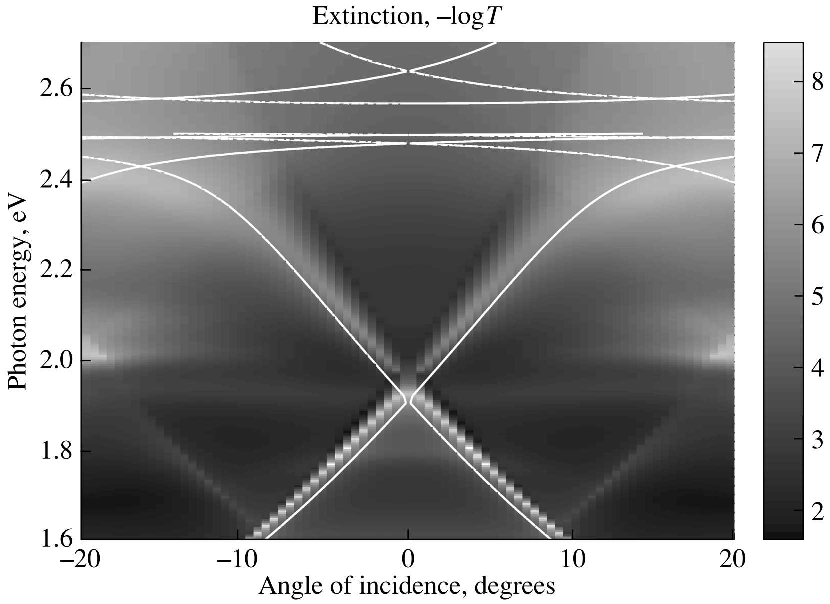

Fig.4. Calculated extinction spectra (see the grey bar for the explanation of the extinction scale). 151 spatial harmonics were taken. White lines: the folded SPP dispersion curves for a flat air-gold interface

We obtain Re $\hbar\omega_l = 2.505$ eV and Re $\hbar\omega_u = 2.564$ eV. The corresponding wavelengths are $\lambda_l = 495$ nm and $\lambda_u = 483$ nm. On the other hand, there is obviously no gap if we calculate complex k using real ω (see dashed line in Fig.3a). One can see that the difference between the results obtained via neglecting imaginary parts of ω and k becomes significant at $\hbar\omega > 2.2$ eV in case of gold.

Due to the periodicity of the structure, all the wavevectors that differ by a reciprocal lattice vector are equivalent. Thus, we can rewrite Eq. (1) as

$$\left(k - \frac{2\pi m}{d}\right)^2 = \frac{\omega^2}{c^2}\frac{\varepsilon(\omega)}{\varepsilon(\omega)+1}, \tag{3}$$

where d is the period, and m is an integer number (we consider 1D lattices here). Knowing k and the real part of the frequency ω, we can calculate the corresponding angles of incidence θ_m where we expect to see the SPP-caused features in the spectra via

$$\sin\theta_m = \frac{c\,(k - 2\pi m/d)}{\mathrm{Re}\,\omega}. \tag{4}$$

We expect an almost non-dispersive behavior of plasmonic resonances in the vicinity of $\hbar\omega_l$. Unfortunately, the imaginary part of the resonant frequency is rather large (about 0.3 eV) at these frequencies (Fig.3b), and the absorption is large, too. Hence, the transmittance is much less than 1. Nevertheless, if we consider the extinction spectra (extinction is defined here as $-\log T$, where T is transmittance), we can distinguish the energy-angle positions of the resonances. Figure 4 shows a comparison of the numerical results with the predictions of the ELA with a non-Drude dielectric function and the folded polaritonic-like dependence Re $\omega(k)$. Evidently, the ELA can reproduce the numerical results for energies below 2.5 eV ($\lambda > 500$ nm). The numerical results were obtained by an optical scattering matrix approach [4] with important improvements [11], i.e., the factorization rules [12] and adaptive spatial resolution [13]. Furthermore, the results are in a good agreement with the experimental data given in [6]. For higher energies the enhanced absorption unfortunately smears out all the features.

There are also some other features in the spectra, e.g., the Wood-Rayleigh anomalies (see discussion in [6]) and the SPPs on the interface of quartz and gold. However, the main peculiarities are due to the excitation of the SPPs on the interface of air and gold.

To conclude, in our letter we show that using the Lorentz-Drude model for the dielectric function of gold we can apply the ELA to the SPP dispersion relation for predicting the positions of the peculiarities of the extinction spectra of the structure in a wider spectral range, including the vicinity of the d-band in gold. The interband electron transitions in gold and the spatial periodicity of the structure and incoming light waves lead to a polaritonic-like dispersion law of the resonances. Numerical simulations with the improved scattering matrix method confirm the polaritonic-like behavior of the SPP dispersion law Re $\omega(k)$ in gold.

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1. W. L. Barnes, A. Dereux, and T. W. Ebbesen, Nature **424**, 824 (2003).
2. D. R. Smith, J. B. Pendry, and M. C. K. Wiltshire, Science **305**, 788 (2004).
3. V. M. Shalaev, Nature Photonics **1**, 41 (2007).
4. S. G. Tikhodeev, A. L. Yablonskii, E. A. Muljarov et al., Phys. Rev. B **66**, 045102 (2002).
5. N. A. Gippius, S. G. Tikhodeev, and T. Ishihara, Phys. Rev. B. **72**, 045138 (2005).
6. A. S. Vengurlekar, Opt. Lett. **33**, 1669 (2008).
7. U. Fano, J. Opt. Soc. Am. **31**, 213 (1941).
8. A. D. Rakić, A. B. Djurišić, J. M. Elazar, and M. L. Majewski, Appl. Opt. **37**, 5271 (1998).
9. P. B. Johnson and R. W. Christy, Phys. Rev. B **6**, 4370 (1972).
10. V. M. Agranovich, *Theory of excitons*, M.: Nauka, 1968.
11. T. Weiss, G. Granet, N. A. Gippius et al., Opt. Exp. **17**, 8051 (2009).
12. L. Li, J. Opt. Soc. Am. A **13**, 1870 (1996).
13. G. Granet, J. Opt. Soc. Am. A **16**, 2510 (1999).