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Optical Properties of One-Dimensional Subwave Plasmonic Nanostructures

A. V. Andreev[a], Yu. V. Grishchenko[b], M. I. Dobynde[a], T. V. Dolgova[a], M. L. Zanaveskin[b], A. A. Konovko[a], D. A. Mamichev[b], A. N. Marchenkov[b], E. G. Novoselova[c], I. A. Chernykh[b], I. S. Smirnov[c], A. A. Fedyanin[a], and M. R. Shcherbakov[a]

[a] *Faculty of Physics, Moscow State University, Moscow, 119992 Russia*
e-mail: konovko@physics.msu.ru
[b] *Russian Research Centre Kurchatov Institute, pl. Akademika Kurchatova 1, Moscow, 123182 Russia*
[c] *Moscow State Institute of Electronics and Mathematics (Technical University), Moscow, 109028 Russia*

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Nanogratings formed by parallel gold nanowires on a quartz substrate have been fabricated. Their transmission and reflection spectra have been studied experimentally. Numerical simulation of the transmission (reflection) spectra has been performed. The simulated spectra agree well with the experimental ones. A package has been proposed, which combines the experimental techniques of the structure fabrication and theoretical methods for calculating the parameters of optical spectra. This package is a promising tool for designing and fabricating optoelectronic devices such as filters, polarizers, and switches.

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Development of new optoelectronic systems is closely related to the problem of making miniature optical gauges and control components. In this regard, subwave nanogratings, i.e., the artificial gratings on a substrate surface, at least one spatial size of which is much smaller than the wavelength of diffracting radiation, are of great interest. Metallic nanogratings with the said parameters have a number of properties that make them promising for making next-generation fast miniature biosensors [1] and compact optical control components. Those include anomalous transmittance [2], anomalous opacity [3], artificial optical and magnetooptical activity [4], and the possibility of plasmon focusing [5–9].

The elaboration of compact sensors and optoelectronic devices is tightly bound to the necessity of obtaining reproducible resonance characteristics in the spectrum range of interest. In this respect, it is important to take into account a number of factors that affect physical and structural properties of fabricated nanocomposites. This concerns the choice of materials with required properties and optimization of the grating structure with respect to the period, width, and height of nanowires.

The aforementioned problems cannot be solved without the development of theoretical models that explain the dependence of the position of resonances on mentioned structural and material parameters. Thus, purposeful fabrication of nanostructures with well-controlled and reproducible properties requires the development of a package of theoretical methods for calculating optical spectra and experimental techniques for producing the corresponding nanostructures. In this work, we develop a theoretical model that allows one to find the position of resonances in the kinematic approximation, and mathematical methods for exact numerical calculation of frequency–angular spectra. Experimental samples of nanostructures were fabricated and their spectra were measured. The results of measurements agree well with the theoretical calculations. Further development of the proposed package will allow one to design nanostructures with required resonance characteristics and then to fabricate them with the use of the experimental techniques described in this work.

MATHEMATICAL SIMULATION

Let us consider a nanostructure formed by parallel rectangular gold nanowires on a quartz substrate (a nanograting). In this work, optical spectra of such nanogratings are calculated by the method of eigenmodes of a periodic grating [10, 11]. Figure 1 shows the energy transmittance and reflectance as functions of the wavelength of incident light for the grating with period $d = 750$ nm, wire spacing $c = 100$ nm, and height $h = 50$ nm at an angle of incidence of $\theta = 45°$ and a substrate permittivity of $\varepsilon = 2.13$. As is seen in Fig. 1, the wavelength dependence of reflectance R_0 is nonmonotonic and has a number of dips. The deepest one is located at a wavelength of $\lambda = 816$ nm. Its FWHM is $\Delta\lambda \approx 0.0199$ nm, which corresponds to $\Delta\lambda/\lambda \approx 1.44 \times 10^{-5}$. The slope of the long-wavelength side of this resonance is 46.68 μm^{-1}, which provides

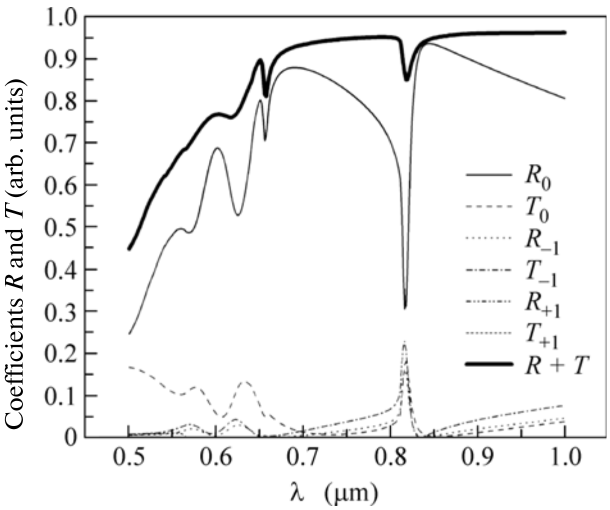

Fig. 1. Energy reflectance and transmittance of a gold grating on a quartz substrate with the parameters $d = 750$ nm, $c = 100$ nm, and $h = 50$ nm at an angle of incidence of $\theta_0 = 45°$.

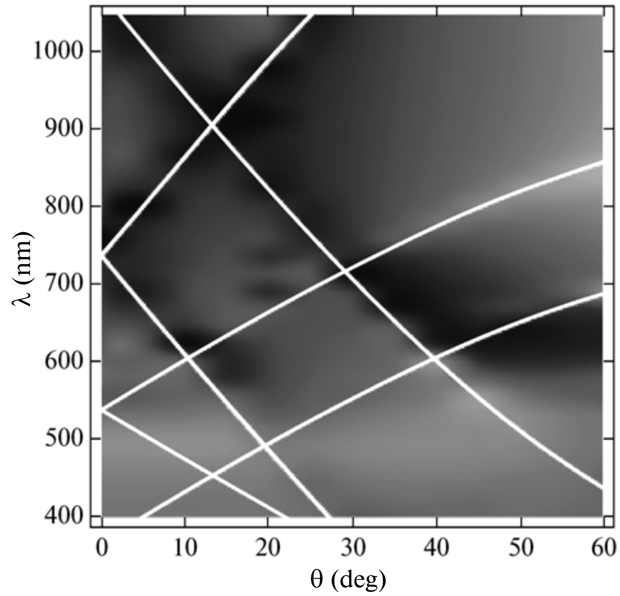

Fig. 2. Traces of dispersion surfaces that determine diffraction of the incident wave on the grating (interaction with the reciprocal lattice vector $H = 2\pi/d$) and diffraction of the reflected wave due to interaction with the first (H) and second ($2H$) harmonics of the grating. The grating period is $d = 740$ nm, the distance between the gold wires is $c = 100$ nm, and the profile depth is 50 nm.

effective frequency modulation of reflected light because a $\delta\lambda = 0.012$ nm ($\Delta\lambda/\lambda \approx 1.4 \times 10^{-5}$) change in the wavelength leads to a change in the reflected beam intensity by a factor of three. On the other hand, according to calculations, the same change in the wavelength leads to an almost complete suppression of the transmitted wave and its ±1-order reflections.

Thus, the grating under consideration is a highly selective filter for the 816-nm light, which provides effective intensity control of reflected and transmitted radiation.

The wavelength dependence of the sum of transmittance and reflectance is also nonmonotonic. As is seen in Fig. 1, its decrease at short wavelengths is basically due to off-resonance absorption by gold. However, two deep minima coinciding with the ones in the reflectance curve have a clear resonance profile. As will be seen below, they are associated with the excitation of surface plasmons.

To interpret the above resonance behavior of reflectance and transmittance, let us consider the dependence of these quantities on the wavelength and angle of incidence shown in Fig. 2. White solid lines in Fig. 2 are the conditions of the resonance excitation of surface waves, the so-called surface plasmon-polaritons, which are the collective oscillations of the electromagnetic radiation and free-electron plasma in metal [12]. These conditions in the kinematic approximation have the form $H_{\pm n} \pm \kappa \sin\theta_0^{(\pm n)} = \kappa$ and $H_{\pm n} \pm \kappa \sin\theta_0^{(\pm n)} = \kappa\sqrt{\epsilon}$ for the grating–air and grating–substrate interfaces, respectively. Here, $\kappa = \omega/c$ is the absolute value of the wave vector in vacuum, $H = 2\pi n/d$, and ϵ is the permittivity of the substrate. Clearly, the kinematic approximation holds in a pretty wide range of parameters shown in Fig. 2. Deviations appear in the regions where the effects of dynamic scattering, e.g., polariton scattering by the second harmonic of the grating profile, emerge. Thus, the sharp peaks and dips in Fig. 1 are caused by the excitation of surface waves.

The aforementioned results demonstrate high spectral selectivity of the subwave grating and indicate good prospects of using nanogratings as frequency–angle optical filters and sensor components.

NANOGRATING FABRICATION TECHNIQUE

As is known, a subwave diffraction grating capable of demonstrating plasmon resonance is a periodically modulated metal surface in the dielectric environment. According to the analysis of adhesion of materials to each other, permittivity, inertness, free-charge-carrier density, and other factors, gold is an optimal material for such structures. The dielectric substrate was made of quartz, which has advantages of high transmittance and the absence of dispersion in an optical band.

Experimental samples were made in two stages by (a) magnetron sputtering of a thin gold film onto a quartz substrate and (b) lithographic fabrication of periodic nanostructures in the gold film by focused ion beams with the use of a FEI Helios two-beam setup.

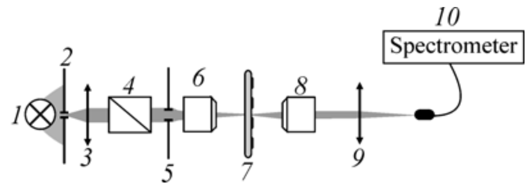

Fig. 3. Scheme of the transmission microspectroscopy setup with the (*1*) 100-W bulb lamp, (*2*) field diaphragm, (*3*) condenser lens, (*4*) Glan–Taylor prism, (*5*) aperture diaphragm, (*6*) objective, (*7*) sample, (*8*) collecting objective, (*9*) collecting lens, and (*10*) fiber-optic spectrometer.

According to in situ X-ray reflection spectroscopy, the thickness of the sputtered gold film was 30 nm.

The samples were metallic nanogratings made of alternating gold wires and etched strips. The main characteristics of the nanogratings are the period, which was 750 nm in our case, and the grating filling factor, i.e., the ratio of the initial volume of the gold film to the volume of the etched material, ranging from 35 to 80%. The area of each grating was 100 μm^2.

The series of samples was investigated by scanning electron and atomic-force microscopy. The grating period and the width of gold wires were found to be 750 ± 10 and (350–600) ± 10 nm, respectively. The depth of etched strips was 40 nm; this is greater than the film thickness and, thereby, ensures complete elimination of gold from the substrate (we took into account redeposition and the presence of possible inhomogeneities in the gold film).

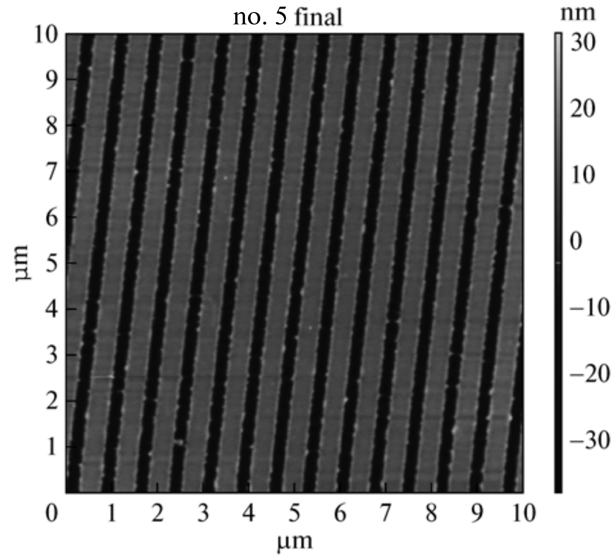

Fig. 4. Atomic-force microscopy image of a nanograting with a period of 750 nm and a filling factor of 65%.

EXPERIMENTAL RESULTS

The optical properties of the fabricated nanogratings were experimentally studied by transmission microspectroscopy (Fig. 3) with the use of a white light source in a spectral range of 400–1000 nm. Radiation of the 100-W bulb lamp polarized by a broadband Glan–Taylor prism passed through a system of lenses and diaphragms and formed a 50-μm image of a field diaphragm in the sample plane. To limit the angular composition of the radiation of the illuminating system, the aperture of the focusing system was reduced to 0.05, which provided a high-contrast resolution of plasmon resonances of the sample in the above spectral range. The radiation was further collected by an objective and focused to the end of a mul-

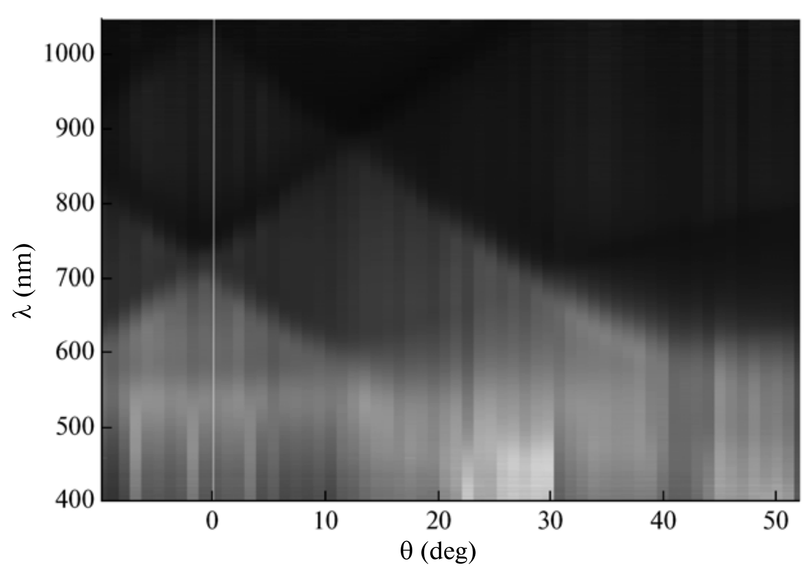

Fig. 5. Experimental spectral transmittance versus the angle of incidence θ. Dark and light regions correspond to a lower (a minimum value of 0.08) and higher (a maximum value of 0.99) transmittance, respectively.

timode optical fiber, which transmitted the radiation to the entrance slit of a spectrometer based on a silicon CCD array.

A typical image of a nanograting is shown in Fig. 4.

Figure 5 presents the experimental dependence of the spectral transmittance on the angle of incidence. The picture consists of overlapping maxima and minima of the transmittance, which are associated with plasmon absorption and plasmon-assisted transmission. The minima and maxima of the transmittance correspond to Wood's anomalies, which appear under the condition of the effective excitation of surface waves.

CONCLUSIONS

Subwave nanostructures formed by gold nanogratings on a melted-quartz substrate have been fabricated. The resonance features observed in the angular dependence of the transmittance of the nanograting are caused by the effective excitation of surface plasmons at the metal–air and metal–dielectric interfaces. The theoretical model describing the behavior of the optical characteristics has been proposed. Experimental results agree well with the theoretical dependences. The complex approach proposed in this work and including nanostructure calculation and fabrication techniques allows one to design the parameters of subwave plasmonic nanogratings. Development of this approach is a necessary step on the way towards manufacturing the whole set of devices based on the excitation of plasmon-polaritons, e.g., next-generation fast high-sensitivity biosensors, as well as optoelectronic components such as filters, polarizers, and switches.

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