Wood anomalies for *s*-polarized light incident on a one-dimensional metal grating and their coupling with channel plasmons

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Angular spectra of reflectance of light from one-dimensional periodic gratings of V-shaped grooves in a metal film have been theoretically studied at a fixed wavelength. The exciting light wave was incident in the plane parallel to grooves. For the case of *s*-polarized incident wave there are two types of features (dips) in reflection spectra. The first type is associated with the excitation of channel plasmons in every single groove of a grating. Angular positions of features of the second type are determined by a period of a grating. We have shown that the features of the second type are Wood anomalies associated with the excitation of surface waves on a metal film by means of diffraction of the incident wave on a periodic grating. For certain periods of a grating and angles of incidence of the exciting wave the resonances of two types can be coupled.

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I. INTRODUCTION

Great interest in plasmonics of nanostructured surfaces and films results from many applications in, e.g., sensing [1–4], surface-enhanced Raman scattering [5,6], thin highly absorptive films [6–8] and various metasurfaces with predefined characteristics of reflection [9–13], control of surface wave propagation with plasmonic photonic crystals [14,15], and excitation of surface waves by far field (along with excitation in the Kretschmann configuration) [1,16,17].

One of the first discoveries in the field of plasmonics of nanostructured surfaces was made in 1902 by Wood who studied reflection spectra of diffraction gratings in the form of parallel grooves on a metal surface [18]. Wood found features (narrow maxima and minima) in reflection spectra of a *p*-polarized wave (incident in the plane perpendicular to grooves). The features were named "Wood anomalies" because they could not be explained at that time. For *s*-polarized incident light similar features were absent, however.

Later on, many experiments were carried out confirming Wood's observations and discovering some new peculiarities of reflection spectra [19–21]. In particular, Wood anomalies can indeed be observed only for *p*-polarized incident waves in the case of gratings with shallow grooves (much less than wavelength) [22]. However, for gratings with rather deep modulation, Wood anomalies were also found for *s*-polarized incident waves [19,21]. Wood anomalies were observed for gratings periodic in one or two directions [23,24].

The theory of Wood anomalies that is now common is proposed by Hessel and Oliner in [25]. According to the theory, Wood anomalies are associated with the excitation of surface waves on periodically structured surfaces or films. Surface waves are excited due to coupling with evanescent diffraction lobes of an incident wave diffracted from a periodic grating. The theory developed in [25] explains the absence of Wood anomalies for an *s*-polarized incident wave for the case of shallow gratings. Moreover, this theory justifies the possible existence of Wood anomalies for an *s*-polarized incident wave for the case of deeply modulated gratings.

In the elucidating work [24] on shapes of Wood anomalies reflection and transmission spectra of metal films periodic in two directions are considered. The results in [24] are in line with the results in [25,26] and also confirm the theory of Wood anomalies as resonances associated with the excitation of surface waves on periodic gratings. According to [24], reflected waves are an interference of a resonant and a nonresonant component. The first component is composed of leaky Bloch harmonics of a surface wave resonantly excited by an incident wave due to diffraction from a periodic grating. These leaky harmonics are those Fourier harmonics of the Bloch function (describing the surface wave) that have wave vectors of magnitude less than the wave numbers of plane waves in the surrounding space. The second—nonresonant—component is the result of nonresonant scattering of the incident wave from the metal film. Therefore, a Wood anomaly has in general the asymmetric shape of Fano resonance.

Recently, many works on optical properties of periodically nanostructured surfaces and films have been published [23,27–41]. However, in most of the works devoted to consideration of one-dimensional gratings, the case of waves incident in the plane perpendicular to grating grooves is analyzed. On the other hand, in the configuration when the plane of incidence of an exciting wave is parallel to grooves, channel plasmons in the grooves can be excited [42–44]. It is interesting to analyze if any grating resonances (such as Wood anomalies) exist in this configuration and to study the possible coupling of grating resonances and resonances corresponding to the excitation of channel plasmons.

In the present paper, we theoretically study reflection of light from periodic arrays of parallel V-shaped grooves in metal films. The plane of incidence (the yz plane) of exciting waves is parallel to grooves [see Fig. 1(a)]. We focus our attention on resonances in reflection spectra and coupling between them. The presence of several resonances in reflection spectra may

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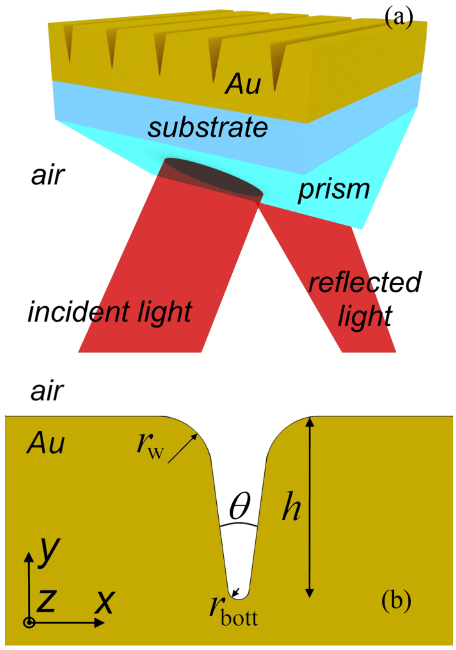

FIG. 1. (a) The system under consideration and the incident and reflected waves (the Kretschmann configuration is realized). (b) The transverse section of a V-shaped groove: the color (yellow online) area represents gold and the white area above gold corresponds to air.

be useful in applications for sensing [45]. This topic will be briefly discussed in Sec. VI.

In Sec. II, the geometry of a system under consideration is described including the cross section of the grooves. Then, in Sec. III, scattering of a plane wave on a metal film with only one groove is studied for different polarizations of the incident wave. This will help to understand for which polarization of the incident wave scattering on a sole groove and therefore on a grating of grooves is more pronounced. Reflection spectra of gratings of grooves are analyzed in Sec. IV showing two types of resonances. Coupling of resonances of the two types is analyzed in Sec. V.

II. GEOMETRY OF GRATINGS AND CONFIGURATION OF INCIDENT WAVES

In this paper, we consider incidence of a plane wave on a periodic grating of V-shaped grooves in a metal film on a dielectric substrate. The exciting wave is incident from the substrate [the Kretschmann configuration is realized; see Fig. 1(a)]. The particular case of gold and fused silica is taken for metal and for substrate, respectively. We analyze angular spectra of reflectance at a fixed wavelength, for the particular case of $\lambda = 632.8$ nm. Nevertheless, the qualitative results of our paper are valid for any wavelength at which surface plasmon polaritons (SPPs) at a metal-air and a metal-substrate interface exist and when $|\varepsilon'| \gg \varepsilon''$ for the permittivity of metal. We take the permittivity of gold $\varepsilon_{\mathrm{Au}} = -11.79 + 1.22i$ at $\lambda = 632.8$ nm [46] and the permittivity of fused silica $\varepsilon_{\mathrm{sub}} = 2.123$. The thickness of the gold film is $d = 100$ nm.

The transverse section of grooves under consideration is shown in Fig. 1(b). The grooves have a depth of $h = 70$ nm with a finite curvature radius of $r_{\mathrm{bott}} = 5$ nm of the gold surface at the bottom [see Fig. 1(b)]. An angle between the sidewalls of the grooves is of $\theta = 15^\circ$ and the curvature radius at the side edges (wedges) of $r_w = 20$ nm. For the chosen wavelength and geometric parameters the groove supports only one channel plasmon mode [42,43] with the wave number $k_{\mathrm{gr}} = (1.104 + 0.092i)k_0$ (calculated by use of COMSOL MULTIPHYSICS). $k_0 = 2\pi/\lambda$ is the wave number in air.

Characteristics of individual grooves influence reflection spectra of gratings of grooves considerably. For instance, different response of grooves to different polarizations of incident waves (in particular, originating from the existence of channel plasmon modes in grooves, which can be excited only by an s-polarized wave [44]) leads to a strong polarization anisotropy of reflection spectra of gratings. Before consideration of reflection spectra of gratings, we first analyze scattering of s- and p-polarized waves on a gold film with only one groove. This will help to understand for which polarization of the incident wave diffraction on gratings of grooves is more pronounced.

III. SCATTERING OF A PLANE WAVE ON A SOLE GROOVE IN A METAL FILM

Let us consider the structure as depicted in Fig. 1(a), but with only one groove in the gold film. The plane of incidence of the exciting wave is again parallel to the groove. In order to evaluate the efficiency of scattering of the incident wave on a sole groove we calculated a value

$$\sigma = \left(\int_{\Sigma} \mathbf{S}_{\mathrm{scat}} \cdot d\mathbf{s} + \frac{ck_0}{8\pi} \int_V \varepsilon'' |\mathbf{E}_{\mathrm{scat}}|^2 dv \right) \Big/ I_{\mathrm{inc}},$$

which is in some sense an effective scattering cross section of the groove per its unit length. Here and below, all the numerical calculations were performed by use of COMSOL MULTIPHYSICS. In the expression for σ I_{inc} is the intensity of the incident wave, $\int_{\Sigma} \mathbf{S}_{\mathrm{scat}} \cdot d\mathbf{s}$ is the flux of the Poynting vector $\mathbf{S}_{\mathrm{scat}}$ through a cylindric surface Σ surrounding the groove and having the unit length along the z axis (see Fig. 2). The Poynting vector $\mathbf{S}_{\mathrm{scat}}$ for the scattered field was calculated

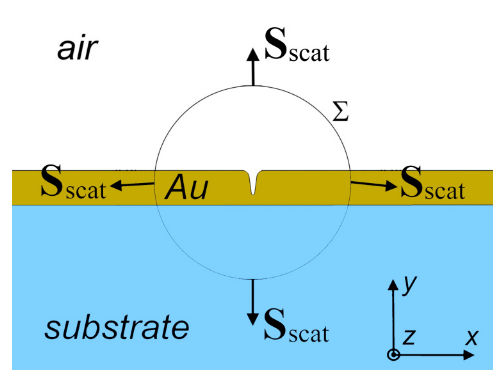

FIG. 2. The surface Σ of integration of the flux of the Poynting vector $\mathbf{S}_{\mathrm{scat}}$ for the evaluation of the effective scattering cross section of a sole groove (per its unit length). This surface is cylindric with the cylinder axis along the z axis; the cross section (with the shape of circle) of the surface Σ by the xy plane is shown.

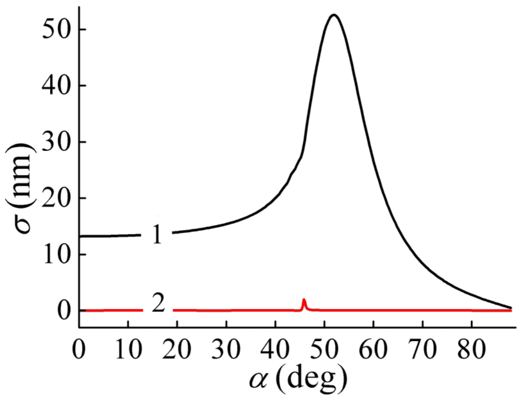

FIG. 3. The effective scattering cross section σ of a sole groove versus the angle of incidence α of the exciting wave. Curve 1 is for the s-polarized incident wave; curve 2 is for the p-polarized incident wave.

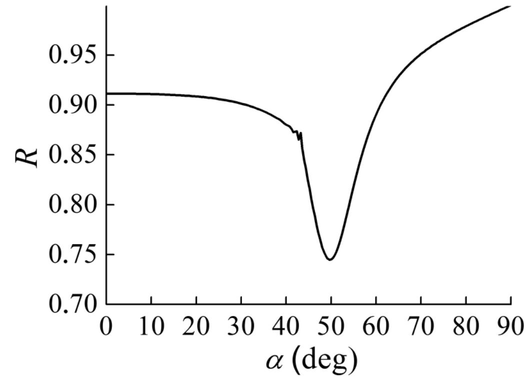

FIG. 4. The angular spectrum of specular reflectance R of the s-polarized incident plane wave at a fixed wavelength. The wave is incident on the array of grooves with the period $D = 300$ nm. The grooves parameters are specified in Sec. II.

as $\mathbf{S}_{\text{scat}} = (c/8\pi)\text{Re}[\mathbf{E}_{\text{scat}} \times \mathbf{H}^*_{\text{scat}}]$. Here the scattered electric field $\mathbf{E}_{\text{scat}}$ is the difference between the full electric field with the presence of the groove and the electric field for the case of a flat gold film without the groove. The scattered magnetic field $\mathbf{H}_{\text{scat}}$ is determined by analogy. The second (volume) integral in the formula for σ expresses the Ohmic loss power of the scattered field inside the volume V confined by the surface Σ and having the unit length along the z axis. This second integral is added in the expression for σ in order for σ to be independent on the particular size and shape of Σ (this independence is confirmed by our calculations). Specifically, when Σ matches the shape of the groove and there is no gold inside the integration volume V the second integral in the expression for σ vanishes and σ becomes the flux of $\mathbf{S}_{\text{scat}}$ through Σ (divided by I_{inc}). The dependences of σ on the angle α of incidence of the exciting wave are presented in Fig. 3 for s- and p-polarized exciting waves. Here and below α is the angle between the normal to the gold film and the wave vector of the incident wave in the substrate.

In Fig. 3, one can see that for all α the effective cross section σ is much larger for the s-polarized incident wave than for the p-polarized one. For this reason, we anticipate diffraction on gratings of grooves (and therefore possible grating resonances) to be more pronounced for the case of the s-polarized incident wave. Indeed, the groove under consideration has a rather small corner angle $\theta = 15^\circ$ and the sidewalls nearly vertical (almost perpendicular to the x axis). And it is an s-polarized incident wave with the electric field nearly perpendicular to the sidewalls of the groove (along the x axis) that is scattered much stronger.

The peak of σ near $\alpha = 52.0^\circ$ for the s-polarized incident wave is, most likely, correspondent to the excitation of a channel plasmon in the groove. Indeed, $\alpha = 52.0^\circ$ approximately meets the condition of excitation of a channel plasmon $\text{Re}k_{\text{gr}} = k_0 n_{\text{sub}} \sin\alpha$, where $n_{\text{sub}} = \sqrt{\varepsilon_{\text{sub}}}$.

In the next section, angular reflection spectra of gold films with periodic arrays of grooves for various periods D are analyzed. Taking into account the results of the current section, we will consider only s-polarized incident waves below.

IV. ANGULAR REFLECTION SPECTRA OF ARRAYS OF GROOVES FOR s-POLARIZED INCIDENT WAVE

In [44] we study reflection spectra for similar periodic gratings in metal films but put an emphasis on excitation of channel plasmons in grooves. In [44] it is shown that for small enough periods D so as $2\pi/D > \text{Re}k_{\text{SPPsub}}$, there is only one feature (minimum) in the reflection spectra of s-polarized waves. The feature is associated with the excitation of channel plasmons in grooves of a grating and its angular position is weakly dependent on D. In the above inequality $k_{\text{SPPsub}} = k_0[\varepsilon_{\text{Au}}\varepsilon_{\text{sub}}/(\varepsilon_{\text{Au}} + \varepsilon_{\text{sub}})]^{1/2} = (1.609 + 0.018i)k_0$ is the wave number of a SPP on a gold-substrate interface. Note that, if the above given inequality is met, the inequality $2\pi/D > \text{Re}k_{\text{SPPair}}$ is also met, where $k_{\text{SPPair}} = k_0[\varepsilon_{\text{Au}}/(\varepsilon_{\text{Au}} + 1)]^{1/2} = (1.045 + 0.005i)k_0$ is the wave number of a SPP on a gold-air interface. In Fig. 4, the angular spectrum of specular reflectance for an s-polarized exciting wave for $D = 300\text{ nm} < 2\pi/\text{Re}k_{\text{SPPsub}}$ is shown. The minimum at $\alpha = 49.6^\circ$ corresponds to the excitation of channel plasmons in grooves of the array. $\alpha = 49.6^\circ$ approximately meets the condition of excitation of a channel plasmon $\text{Re}k_{\text{gr}} = k_0 n_{\text{sub}} \sin\alpha$.

For $2\pi/D < \text{Re}k_{\text{SPPsub}}$, however, additional features in reflection spectra may appear. This can be seen in Fig. 5, where reflection spectra for $D = 430$ nm and $D = 460$ nm are presented. There are two minima in the spectra. One of them has an angular position of about $\alpha = 53^\circ$ weakly depending on D. This minimum is associated with the excitation of channel plasmons in grooves of the array. On the contrary, the angular position of the minimum near $\alpha = 23.8^\circ$ at $D = 430$ nm considerably changes with the increase of D.

The considerable shift of the minimum from $\alpha = 23.8^\circ$ at $D = 430$ nm to $\alpha = 32.4^\circ$ at $D = 460$ nm indicates that this minimum corresponds to some kind of a grating resonance. The angular positions of the minima are well predicted by the condition $|\mathbf{k}_\parallel \pm \mathbf{G}| = \text{Re}k_{\text{SPPsub}}$ of excitation of a SPP on the gold-substrate interface by means of diffraction on an array of grooves. Here $\mathbf{G}$ is the reciprocal lattice vector directed along the x axis, and $\mathbf{k}_\parallel$ is the z component of the wave vector of the incident wave. The above condition may be reformulated as $k_0^2 n_{\text{sub}}^2 \sin^2\alpha + (2\pi/D)^2 = (\text{Re}k_{\text{SPPsub}})^2$. For $D = 430$ nm the condition gives $\alpha = 26.5^\circ$ and for $D = 460$ nm it gives

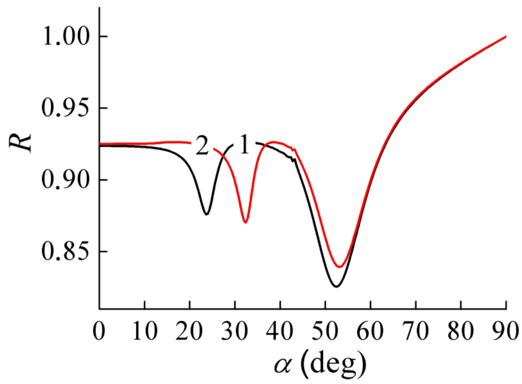

FIG. 5. The angular spectra of specular reflectance R from arrays of grooves for the s-polarized incident plane wave at a fixed wavelength. The grooves parameters are specified in Sec. II. Curve 1 is for $D = 430$ nm, and curve 2 is for $D = 460$ nm.

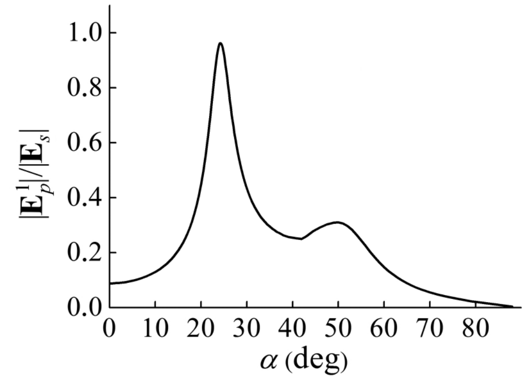

FIG. 7. Ratio of the magnitude $|\mathbf{E}_p^1|$ of the electric field of the p-polarized first-order side diffraction lobe to the magnitude $|\mathbf{E}_s|$ of the electric field of the s-polarized incident wave. The value $|\mathbf{E}_p^1|$ is taken just below the gold-substrate interface. $D = 430$ nm.

$\alpha = 34.8^\circ$; the obtained angles α are close to the actual angular positions of minima in Fig. 5.

In order to make sure that the observed minima correspond to the excitation of SPPs on the gold-substrate interface by means of diffraction on an array of grooves we show in Fig. 6(a) the spatial distribution of the electric field in the structure with $D = 430$ nm at $\alpha = 23.8^\circ$. Specifically, a spatial distribution of magnitude of the electric field y projection (i.e., the quantity of $|E_y|$) is depicted. The reason behind the choice of the quantity is that only p-polarized (like SPPs) side diffraction lobes of the scattered field have nonzero value of E_y (both above and below the gold film) while the incident wave and the specularly reflected one have only E_x nonzero, and s-polarized side diffraction lobes have only E_x and E_z nonzero. In Fig. 6(a), one can see two local maxima of the field along the x axis on the gold-substrate interface. The magnitude of the field decreases rapidly with distance from the gold-substrate interface. Thus, Fig. 6(a) shows that for $D = 430$ nm and $\alpha = 23.8^\circ$ p-polarized side diffraction lobes have much larger amplitude at the gold-substrate interface than at the gold-air interface.

In Fig. 7 the magnitude of the full electric field $\mathbf{E}_p^1$ of the p-polarized first-order side diffraction lobe as a function of α is shown. $|\mathbf{E}_p^1|$ is taken just below the gold-substrate interface. $|\mathbf{E}_p^1|$ normalized by the magnitude $|\mathbf{E}_s|$ of the electric field of the s-polarized incident wave has a pronounced maximum at $\alpha = 24.1^\circ$ which can be treated as resonant excitation of the p-polarized surface wave on the gold-substrate interface.

Thus, we state, the observed minima in Fig. 5 at $\alpha = 23.8^\circ$ for $D = 430$ nm and at $\alpha = 32.4^\circ$ for $D = 460$ nm are some kind of Wood anomalies. Indeed, just as well-known Wood anomalies for p-polarized incident waves [18,25,47], the minima correspond to resonant excitation of a p-polarized surface wave (like a SPP) on a metal surface due to diffraction from a periodic grating. The angular positions of the Wood anomalies for p-polarized incident waves are described by the condition $|\mathbf{k}_\parallel + \mathbf{G}| = k_{\text{surf}}$ [25,47] similar to that specified above for the grating resonances in Fig. 5. Here $\mathbf{k}_\parallel$ is the projection of the wave vector of the incident wave onto the plane of the metal surface, k_{surf}—the wave number of the excited surface wave (e.g., SPP) on the metal surface.

To confirm the statement that the minima at $\alpha = 23.8^\circ$ and at $\alpha = 32.4^\circ$ in Fig. 5 are in fact Wood anomalies we consider a configuration similar to that used in the original experiments of Wood: light is incident on a thick metal with a grating. However, contrary to the case of Wood's experiments [18], the plane of incidence is parallel to grooves in our case (see the configuration in Fig. 8). Also, in our case, the space above gold (also in grooves) is filled with fused silica (with the refractive index n_{sub}) so that the wave vector of the incident wave $|\mathbf{k}_\parallel| = k_0 n_{\text{sub}} \sin\alpha$ is the same for configurations from Figs. 1(a) and 8 for the same α.

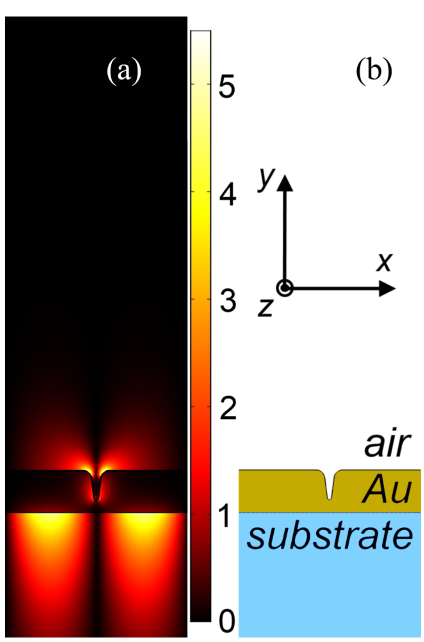

FIG. 6. (a) Spatial distribution of $|E_y|$ in the plane perpendicular to grooves (the xy plane) for the s-polarized wave incident on the structure having $D = 430$ nm at $\alpha = 23.8^\circ$. Only one period of the grating is shown. Color bar to the right of the figure is in arbitrary units. (b) The geometry of the area shown in Fig. 6(a).

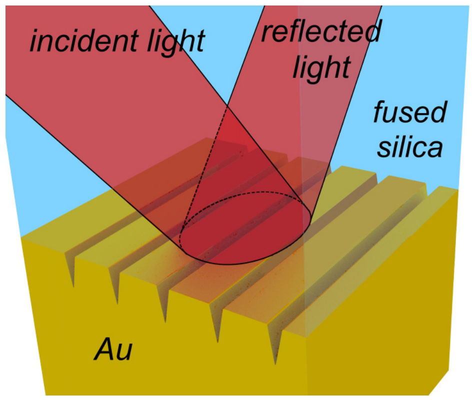

FIG. 8. Reflection of a plane wave from a grating of grooves on a surface of thick gold.

Angular spectra of specular reflectance of the s-polarized incident wave for the configuration from Fig. 8 are shown in Fig. 9 for $D = 430$ nm and $D = 460$ nm. The angular positions of the minima in Fig. 9 are $\alpha = 18.0^\circ$ and $\alpha = 29.2^\circ$ for $D = 430$ nm and $D = 460$ nm, respectively. These values of α are rather close, respectively, to $\alpha = 23.8^\circ$ and $\alpha = 32.4^\circ$ for minima in Fig. 5. Therefore, we may infer that the minima in Figs. 5 and 9 shifting their position are of the same nature. These minima can appear in the case of both thin metal film [as in Fig. 1(a)] and metal half-space (as in Fig. 8). Thus, the minima are in fact Wood anomalies. The reason for the certain difference between angular positions of the Wood anomalies in Figs. 5 and 9 for the same D is in some difference between excited surface waves: the Wood anomalies in Fig. 5 correspond to the excitation of a surface plasmonic wave on the flat gold-silica interface while the Wood anomalies in Fig. 9 correspond to a surface plasmonic wave on the curved gold-silica interface modulated by grooves.

Now let us return to the Kretschmann configuration [Fig. 1(a)]. The further increase of D (up to the values $2\pi/D < k_0$) leads to the appearance of an additional feature in reflection spectra. The angular position of the feature is well expressed by the condition $|\mathbf{k}_\parallel \pm \mathbf{G}| = k_{\rm surf}$ of excitation of a surface wave by means of diffraction on an array of grooves [which may be reformulated as $k_0^2 n_{\rm sub}^2 \sin^2\alpha + (2\pi/D)^2 = k_{\rm surf}^2$]. Here $k_{\rm surf}$ is an effective wave number of the surface wave slightly dependent on D. The $k_{\rm surf}$ lies in the range $1.0004k_0 \leqslant k_{\rm surf} \leqslant 1.027k_0$ for at least 640 nm $< D <$ 1500 nm. Thus we can conclude that this new feature is a Wood anomaly corresponding to the excitation of a surface wave on the gold-air interface, because $k_{\rm surf}$ is close to $k_{\rm SPPair}$ especially for large $D \approx 1.5$ μm.

To summarize, we have shown that in reflection spectra of s-polarized waves Wood anomalies may appear associated with excitation of surface waves on a surface of gold.

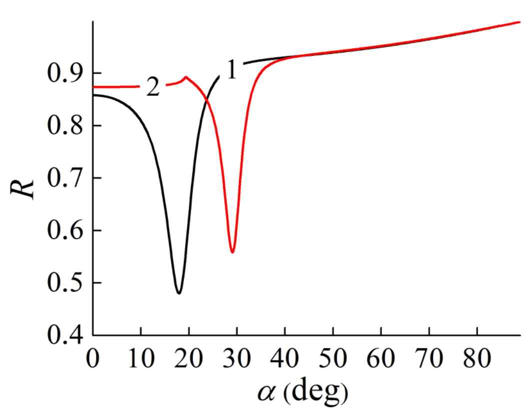

FIG. 9. The angular spectra of specular reflectance R from arrays of grooves for the configuration from Fig. 8 for the s-polarized incident plane wave at the fixed wavelength $\lambda = 632.8$ nm. The grooves parameters are specified in Sec. II. Curve 1 is for $D = 430$ nm, and curve 2 is for $D = 460$ nm.

V. COUPLING OF A WOOD ANOMALY WITH CHANNEL PLASMONS

Now consider angular positions of minima in reflection spectra as functions of period D in the Kretschmann configuration. The functions are presented in Fig. 10 for two minima. The second minimum appears at the condition $2\pi/D \leqslant {\rm Re}k_{\rm SPPsub}$; for even larger D (when $2\pi/D < k_0$) additional minima not indicated in Fig. 10 may appear. The first minimum, which exists even for $2\pi/D > {\rm Re}k_{\rm SPPsub}$, is located near $\alpha = 52.0^\circ$ for all D except for $D \approx 570$ nm. This minimum corresponds to the excitation of channel plasmons in grooves of arrays. Note that $\alpha = 52.0^\circ$ is just the angle of maximal effective scattering cross section σ of a sole groove for the s-polarized exciting wave (i.e., the maximum of curve 1 in Fig. 3), which corresponds to the excitation of a channel plasmon in a sole groove. Then the location of the minimum associated with the excitation of channel plasmons shifts to the angle $\alpha = 52.0^\circ$ with the increase of D. The location of the second minimum of reflection spectra is near the thin solid curve in Fig. 10 for all D except for $D \approx 570$ nm. The thin solid curve is described by the condition $|\mathbf{k}_\parallel \pm \mathbf{G}| = {\rm Re}k_{\rm SPPsub}$ of excitation of a SPP on the gold-substrate interface by means of diffraction from an array of grooves. Thus, we see again that

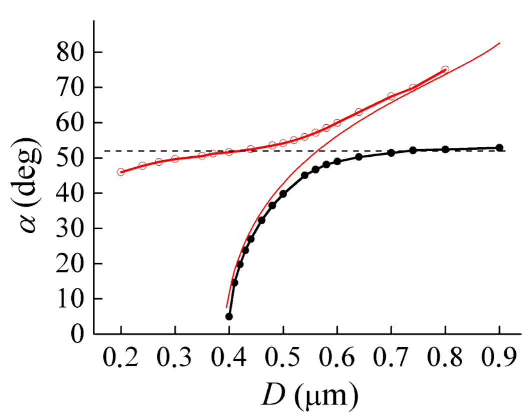

FIG. 10. The solid curves with circles indicate angular positions of minima in specular reflectance spectra as functions of D for the case of the s-polarized incident wave in the Kretschmann configuration [Fig. 1(a)]. The thin solid curve without circles is described by the condition of excitation of a SPP on the gold-substrate interface by means of diffraction from an array of grooves. The horizontal dashed line indicates $\alpha = 52.0^\circ$.

one of the minima (which is at $\alpha = 23.8^\circ$ for $D = 430$ nm) in the reflection spectrum in Fig. 5 (and also indicated in Fig. 10) is a Wood anomaly corresponding to the excitation of a SPP on the gold-substrate interface.

Near $D \approx 570$ nm the thin solid curve in Fig. 10 intersects the horizontal dashed line indicating $\alpha = 52.0^\circ$. For that D the two resonances (corresponding to the excitation of channel plasmons and corresponding to the excitation of SPPs on the gold-substrate interface) couple with each other. As a result, for $D \approx 570$ nm it is impossible to associate one of the two minima with either excitation of channel plasmons or with a Wood anomaly even by inspecting field distributions.

VI. CONCLUSION

To conclude, we have theoretically studied angular spectra of reflectance from one-dimensional periodic gratings of V-shaped grooves in a gold film on a substrate. An exciting wave was incident from the substrate in the plane parallel to grooves (the Kretschmann configuration).

For the case of the s-polarized incident wave, there are two types of features in reflection spectra. The first type is associated with the excitation of channel plasmons in every single groove of a grating. The angular position of the feature of this type is determined by the shape of grooves and weakly depends on a period of a grating. The features of the second type are Wood anomalies and are associated with the excitation of surface waves on surfaces of a gold film due to diffraction of the incident wave from a periodic grating. Angular positions of features of the second type are determined by a period of a grating. For a particular period of a grating features of the first and the second type may occur at close angles of incidence of the exciting wave; for this case the two corresponding resonances become coupled.

The gratings analyzed might find applications in sensing due to strong electric field in grooves (when channel plasmons are excited) or on the interface of the metal film opposite to the substrate (when a surface wave is excited). The presence of at least two minima in reflection spectra may help spatially separate variations of refractive index being sensed [45]. In particular, the field of channel plasmons is localized close to grooves (on the scale of the order of a groove's width [43,44], i.e., of tens of nanometers in our case) thus sensing variations of refractive index in the close vicinity of the metal surface. On the contrary, the shape and the angular position of a Wood anomaly associated with the excitation of a surface wave on the interface between metal and analyzed medium is sensitive to variations of refractive index on a much larger scale. This scale is about depth of penetration of SPP's field into the analyzed medium or more (hundreds of nanometers or microns in our case). A more detailed study of structures similar to those analyzed here for their sensing applications will be presented elsewhere in the future.

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