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*Optics*

# Control of plasmons excitation by *P*- and *S*-polarized light in gold nanowire gratings by azimuthal angle variation

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**Abstract.** We present results of experiments to determine the dispersion of the plasmon modes associated with Au nanowire gratings with a fixed spatial frequency (3370 $mm^{-1}$) and different slits between the nanowires fabricated using an interference (interferometric) lithography technique. Optical properties of fabricated plasmonic structures were studied using measurements of spectral and angular dependence of *P*- and *S*-polarized extinction in the wavelength range 0.4…1.1 µm, angles of incidence 10…70 degrees in conical mounting (at variable azimuth angle within the range $\varphi$ = 0…90 degrees). It has been shown that in the grating with the average slit between the nanowires equal to half of the grating period at $\varphi = 0$ only local plasmons (LP) are excited by *P*-polarized light. When the azimuth angle changes from 0 to 90°, the intensity of the excited LP is smoothly "transferred" from *P*- to *S*-polarized excitation, and at $\varphi$ ~ 30…45 degrees the intensities of the LP bands in both polarizations are approximately equal. However, in the sample with narrow slits between the nanowires (40 nm) we observe the mixed mode with excitation both surface plasmon-polariton (SPP) and LP in the *P*-polarization at $\varphi = 0$. With $\varphi$ rising, the intensity of the mixed mode in *P*-polarization decreases and simultaneously the LP mode intensity in *S*-polarization increases.

**Keywords:** plasmonic gratings, surface plasmon resonance, interference lithography, azimuthal rotation.

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## 1. Introduction

Over the recent few decades, attention of many researchers have been attracted by periodically patterned metal plasmonic nanostructures, including plasmonic gratings (mostly Au or Ag gratings) that have found wide use in numerous fields of research and applications [1-5].

In the gratings with a small relief depth, only surface plasmon-polaritons (SPP) propagate. However, the grating that has large depth of relief or consists of isolated metal nanowires supports several types of fundamental electromagnetic modes, namely [6]: (I) SPPs on a periodic system of nanowires; (II) surface electromagnetic waves along the surface of a single nanowire; (III) cavity modes in the slits between nanowires; (IV) localized plasmon (LP) excitation in the nanowires. Excitation of these modes is defined by system properties, and their interaction leads to redistribution of the oscillator strengths of the separate modes. Excitation of LP and SPP in gold gratings is well studied in literature (including gratings with different depths of modulation and/or slit width between grating grooves [6–10]).

All these studies were performed with the standard method of excitation of plasmons, when the plane of the probing beam incidence was parallel to the grating wave vector (perpendicular to the grating grooves). However, in recent years, the effect of the azimuthal rotation of the plane of incidence on surface plasmon excitation and propagation has been theoretically and experimentally investigated [11-14]. It was shown [12] that at nonzero azimuth more SPPs can be excited with the same illuminating wavelength [13] and sensitivity of grating coupled surface plasmon resonance (SPR) biosensor up to 1000°/RIU is achievable for the second dip in angular interrogation [14], which is more than one order of magnitude greater than in the non-rotated conventional configuration. Azimuthal rotation of the Au chip with a nano-grating surface for SPR biosensor are also used [15] for adjustment the biosensor working range with respect to the refractive index of investigated environment.

Thus, the influence of azimuthal rotation of metal gratings with a small depth of modulation on the properties of the plasmonic response is well studied in literature. But discontinuous systems such as one-dimensional arrays of isolated metal nanowires have not been investigated in such a way yet.

In this work, we experimentally test Au gratings with isolated grooves (arrays of isolated nanowires) for excitation of LP and SPP in conical mounting (at variable azimuth angle). The features of plasmon excitation for *P*- and *S*-polarization of the probing beam in the wide spectral and angular ranges are studied.

## 2. Methods

The samples used for this study were prepared by thermal vacuum deposition of a metal (Au) layer with the thickness 40 to 50 nm and a chalcogenide photoresist layer ($As_{40}S_{40}Se_{20}$) with the thickness close to 100 nm onto polished glass substrates. For the nanostructuring of the gold films, we used interference (interferometric) lithography (IL). This technology was described in more detail in previous works [15, 16].

For the determination of the surface patterns of the etched periodic structure and their dimensions, a Dimension 3000 Scanning Probe Microscope (Digital Instruments Inc., Tonawanda, NY, USA) was used. The spatial frequency of the gratings was determined using the optical stand equipped with a goniometer G5M, which provided the measurement accuracy of ±5 line/mm.

Optical properties of fabricated plasmonic structures were studied using measurements of spectral and angular dependences of transmission and reflection of polarized light. The automated setup for these measurements was described in more detail in the previous paper [10]. These measurements enable to plot the dispersion curves of excited optical modes and to identify their types.

## 3. Results and discussion

Fig. 1 shows the atomic force microscope (AFM) image and cross-section of Au grating formed by IL on the gold layer with the initial thickness close to 40 nm by wet etching through chalcogenide photoresist mask. The period of this grating was 296.6 ± 0.5 nm (spatial frequency $\nu$ = 3370 mm$^{-1}$). This grating was essentially a periodic array of isolated Au nanowires that were not connected by metal interlayer – the average slit between the nanowires was about half of the grating period.

Reflectance (*R*) and transmittance (*T*) spectra of this sample were measured for *S*- and *P*-polarized light within the wavelength range from 0.4 to 1.1 μm and for the angles of incidence (θ) from 10 to 70 degrees. θ is the angle between the normal to the sample surface and the incident beam. These measurements were made for different orientations of the grating grooves relative to the plane of light incidence: the azimuth angle (φ), *i.e.*, the angle between the grating wave vector and the plane of incidence, varied between 0° and 90° with the step 15°.

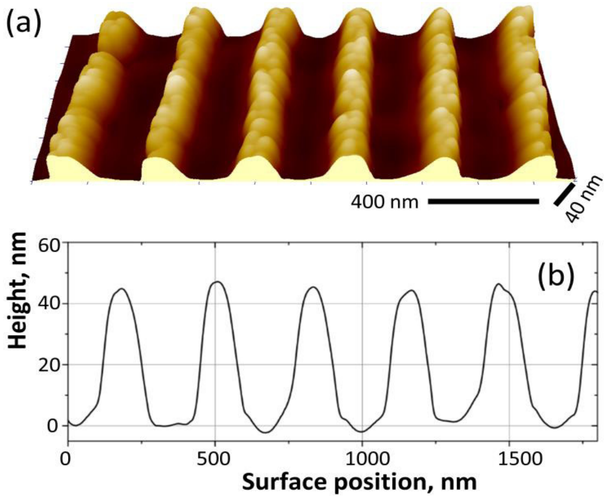


**Fig. 1.** AFM image (a) and cross-section (b) of the Au grating with spatial frequency of 3370 ± 5 mm$^{-1}$ and average value of slit width between nanowires is about 150 nm.

The experimental results are presented through the extinction ($\alpha d$) of the investigated samples, which was estimated using the expression [17]: $\alpha d = \ln((1 - R)/T)$. The obtained values of $\alpha d$ as a function of wavelength and angle of incidence are shown in Fig. 2 for the azimuthal angles 0.45 and 90 degrees. The bands of high extinction can arise as the result of a resonant excitation of SPP and/or LP, mapping thereby the dispersion curves of the plasmon resonances.

Positions of SPP resonances in these coordinates were calculated from the phase-matching condition between $\mathbf{k}_{SPP}$ and $n_1\mathbf{k}_0 \pm m\mathbf{G}$ [18]. Here, $\mathbf{k}_{SPP}$ is the wave vector of SPP, $\mathbf{k}_0$ is the wave vector of the incident radiation with a wavelength λ in vacuum ($k_0 = 2\pi/\lambda$), $n_1 = \sqrt{\varepsilon_1}$ is the refractive index of the environment with the permittivity $\varepsilon_1$, **G** – reciprocal vector of grating with a period $a$ ($G = 2\pi/a$), $m$ is an integer ($m \neq 0$) and denotes the diffraction order. If the azimuthal angle is not equal to zero, then $\mathbf{k}_{SPP}$, $\mathbf{k}_0$ and **G** are no longer collinear and the scalar equation for phase-matching condition becomes [19]:

$$k_{SPP}^2 = n_1^2 k_0^2 \sin^2\theta + m^2 G^2 \pm 2 n_1 m G k_0 \sin\theta\cos\theta . \qquad (1)$$

In the first approximation, to estimate the position of the dispersion curves we used for the grating the same expression for $k_{SPP}$ as for a smooth metal film [18]. With these approximations, the dispersion curves for SPP excited at the interfaces metal/air or metal/substrate were plotted in the coordinates "angle of excitation" versus "wavelength" and are shown by solid lines in Figs. 2 and 5. For these calculations, we took the experimental optical constants of gold measured on the continuous film sa-tellite samples and which are very close to those given in Ref. [20].

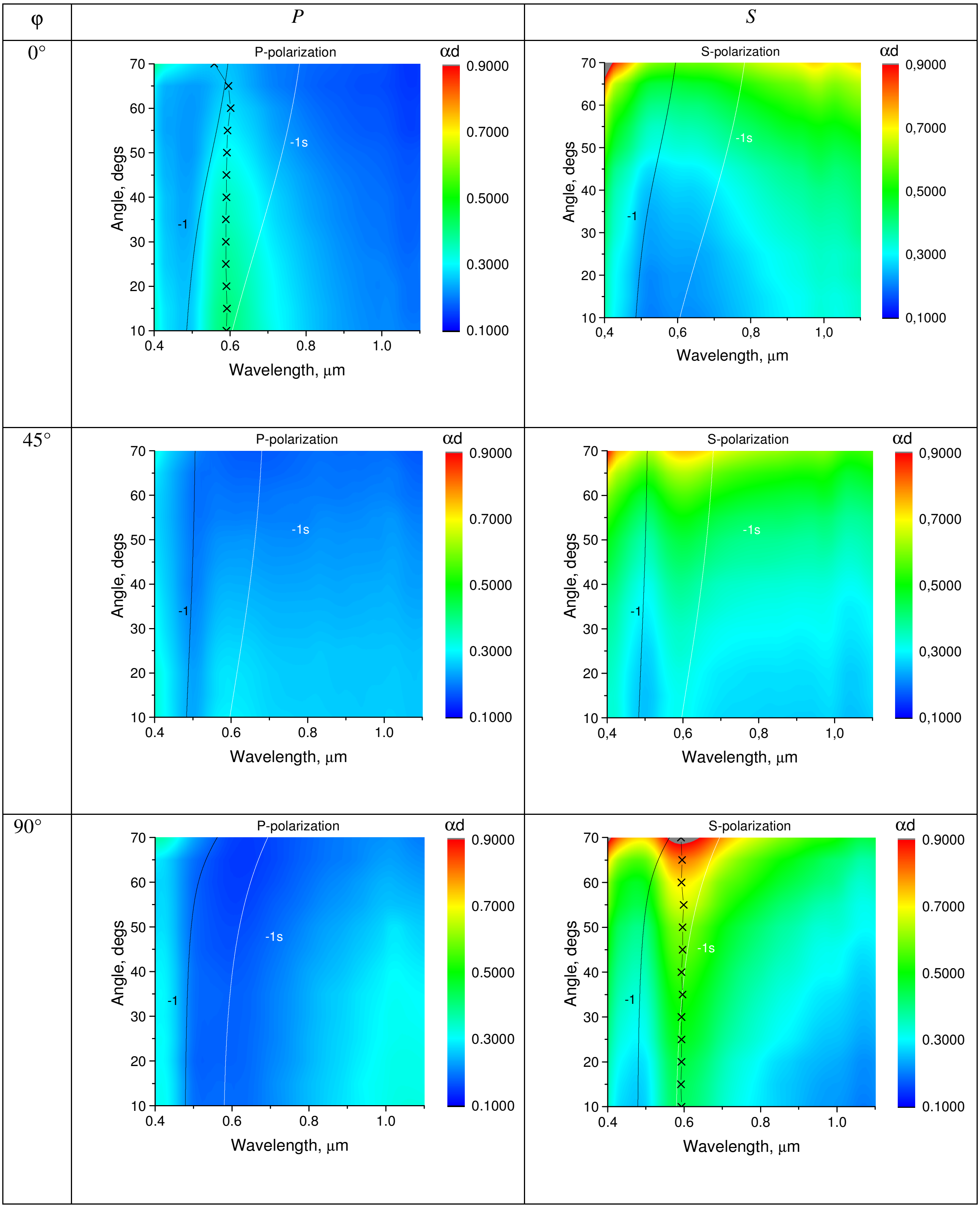


**Fig. 2.** *P*- and *S*-polarized extinction (*αd*) as a function of wavelength and angle of incidence of the Au nanowires grating with the spatial frequency 3370 ± 5 $mm^{-1}$ and average slit between nanowires is about 150 nm for the azimuthal angles 0, 45 and 90 degrees. The experimental data are overlapped with the dispersion curves calculated using Eqs. (1) and (2); the dispersion curves of SPP corresponding to the air-metal interface (–1) and substrate-metal interface (–1s) for $m = -1$ diffraction order. The positions of the maxima of the extinction band are indicated by crosses. The color bar shows extinction with red representing high extinction.

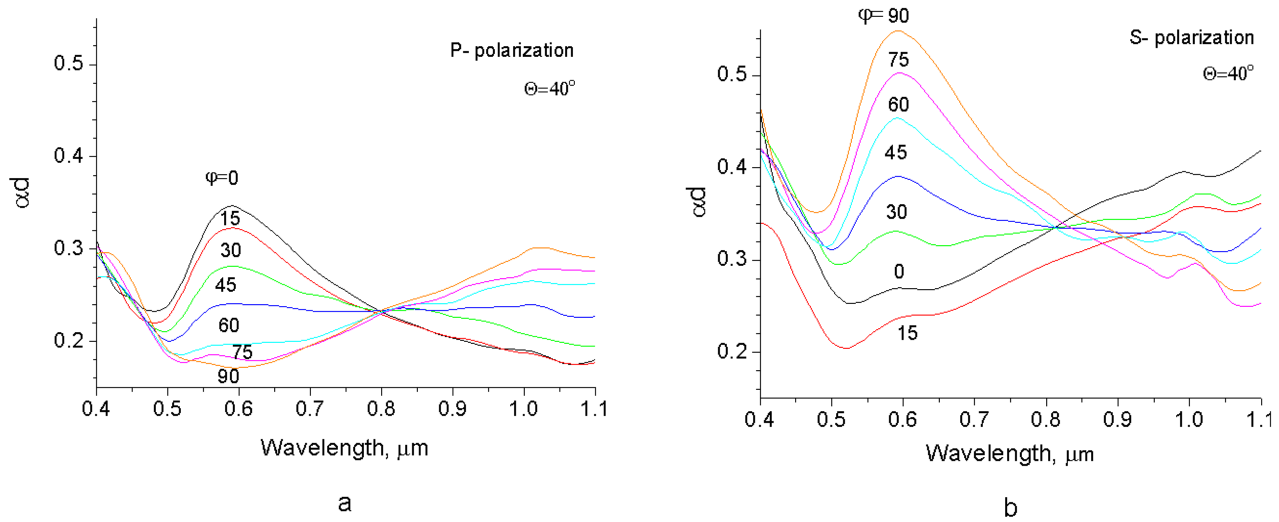


**Fig. 3.** Spectra of extinction (α*d*) at the azimuthal angles from 0 to 90° with the step 15° for *P*-polarized (a) and *S*-polarized (b) light. The angle of incidence (θ) is 40°. The sample with the average slit width between nanowires close to 150 nm.

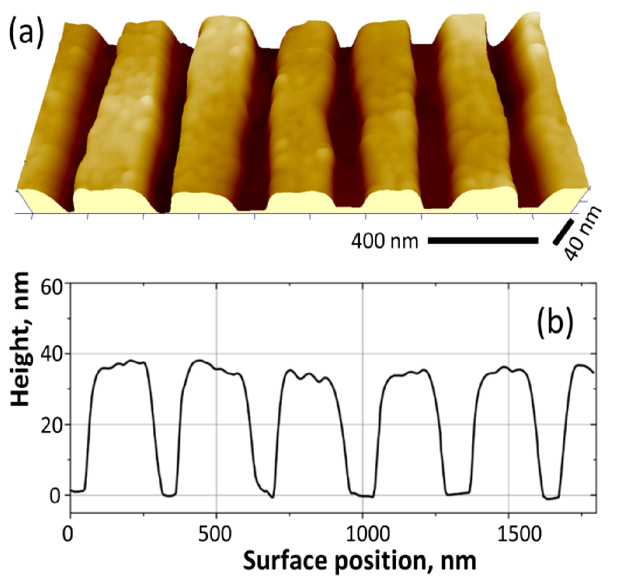


**Fig. 4.** AFM image (a) and cross-section (b) of the Au grating with the spatial frequency 3370 ± 5 $mm^{-1}$ and minimal value of slit width between nanowires (average slit width is about 40 nm).

It can be seen from Fig. 2 that at φ = 0 an intense extinction band is observed in *P*-polarized light, spectral position of which does not depend on the angle of radiation incidence. So, this band does not correlate with the dispersion curves for SPP. But this weak dependence of the resonance spectral position is characteristic for the LP excitation in a periodic array of nanowires [6]. This result agrees with the previous measurements, where it was shown that only local plasmons are excited in the grating of isolated nanowires, when slits between nanowires are wider than the half-period of the grating [10]. At the same time, no extinction bands are observed in *S*-polarization at φ = 0.

With increase of the azimuthal angle, the intensity of this LP band in *P*-polarized light decreases, but an analogous band appears and amplifies in *S*-polarization (Fig. 2).

In more detail, this "transfer" of the intensity of the LP excitation from *P*- to *S*-polarization is shown in Fig. 3. It can be seen that the maximum intensity of the LP band is observed in *P*-polarization at the azimuthal angle 0°, and in *S*-polarization – at 90°. When the azimuthal angle changes from 0 to 90°, the intensity of the excited local plasmon is smoothly "transferred" from *P*- to *S*-polarized excitation, and at φ ~ 30…45 degrees the intensities of the LP bands in both polarizations are approximately equal.

So, for large distances between nanowires the influence of LP-SPP interaction is not essential, and we observe only the LP peak. However, when the slit width between grating grooves decreases, the optical response of the grating may change [10]. Fig. 4 shows the AFM image and the cross-section of periodic array of isolated Au nanowires with the same initial thickness of Au layer and the same period as in Fig. 1 (296.6 ± 0.5 nm), but with the minimal slit between nanowires – the average slit width here is about 40 nm.

The experimental results for this sample (α*d* as a function of wavelength and angle of incidence) are shown in Fig. 5 for the azimuthal angles 0, 45 and 90 degrees. In *P*-polarization at φ = 0, the extinction band is observed, which is intermediate between the spectrally independent LP-band and the SPP dispersion curve corresponding to the substrate-metal interface (–1s). Therefore, we can conclude that this band is the result of LP-SPP interaction in the sample with narrow slits

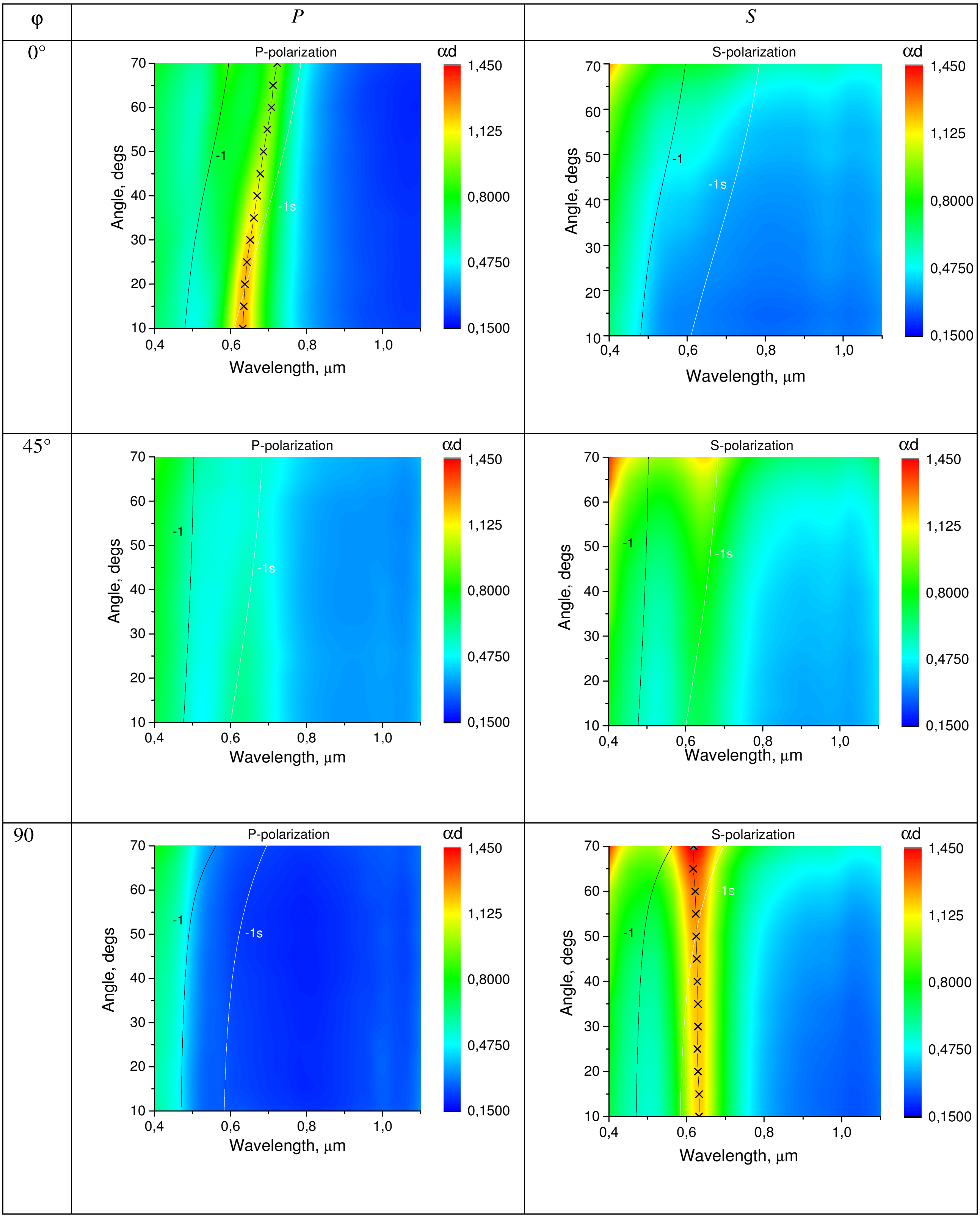


**Fig. 5.** *P*- and *S*-polarized extinction ($\alpha d$) as a function of wavelength and angle of incidence of the Au nanowires grating with the spatial frequency 3370 ± 5 $mm^{-1}$ and average slit between nanowires is close to 40 nm for the azimuthal angles 0, 45 and 90 degrees. The experimental data are overlapped with the dispersion curves like to that in Fig. 2. The positions of maxima for the extinction band are indicated by crosses. The color bar shows extinction with red representing high extinction.

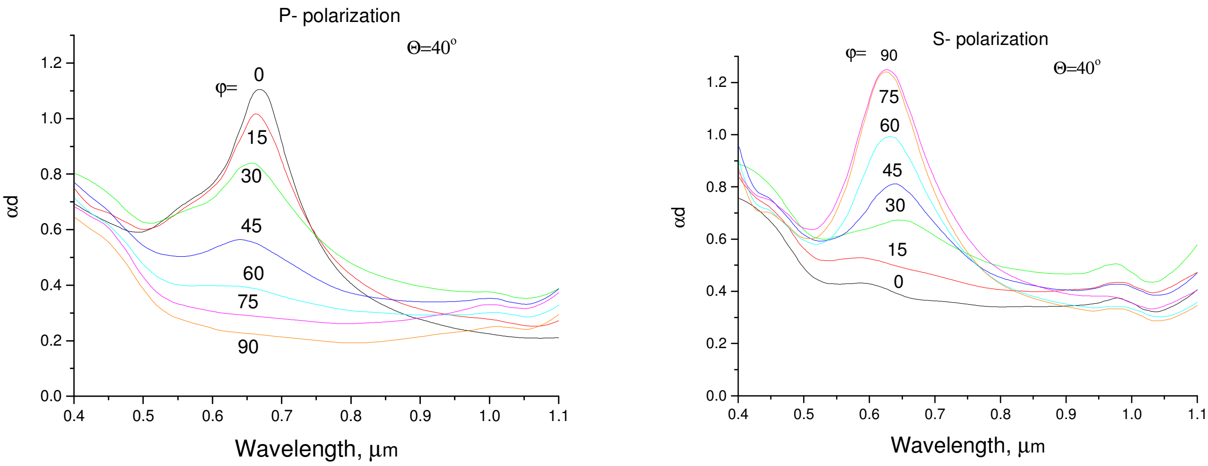


**Fig. 6.** Spectra of extinction (α*d*) at the azimuthal angles from 0 to 90 with the step 15° for *P*-polarized (a) and *S*-polarized (b) light. The angle of incidence (θ) is 40°. The sample with the average slit width between nanowires close to 40 nm.

between the nanowires. We observe the mixed mode with excitation both SPP and LP in this sample. In the sample, no extinction bands are observed in *S*-polarization at φ = 0°, too.

With increasing the azimuth, this composite band in *P*-polarization also weakens, but LP band appears in *S*-polarization, and its intensity reaches the maximum at φ = 90°. Thus, for the sample with small slits between the nanowires, as the azimuthal angle is increased, the mixed LP-SPP mode in *P*-polarization is transformed and "transferred" into pure LP-mode in *S*-polarization.

Fig. 6 shows in more detail the attenuation of the intensity of the mixed mode in *P*-polarization with increasing φ and the simultaneous increase in the intensity of the LP mode in *S*-polarization. Here, also at φ ~ 30…45 degrees the intensities of the bands in both polarizations are approximately equalized.

The results of optical measurements confirm the possibility to control the regimes of plasmons excitation by azimuthal rotation of the grating.

## 4. Conclusions

Using IL technology, we fabricated a set of high-frequency Au gratings with isolated grooves (nanowires) and different slit widths between the nanowires. We have shown that there is smooth transition in the optical response of the gratings with large slits (150 nm) from LP mode in *P*-polarization at small azimuthal angles to the analogous LP resonance in *S*-polarization with increasing the azimuthal angle up to 90 degrees. As the distance between the nanowires decreases, interaction between the LP and SPP modes begins to appear. For the grating with narrow slits (40 nm), the mixed LP-SPP mode is observed in *P*-polarization at φ = 0. With φ rising, the intensity of the mixed mode in *P*-polarization decreases and simultaneously the LP mode intensity in *S*-polarization increases.

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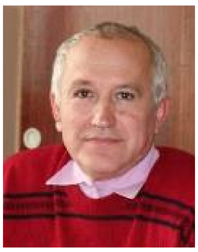

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