Quantum Electronics **47** (1) 65–70 (2017)

SURFACE ELECTROMAGNETIC WAVES https://doi.org/10.1070/QEL16178

Reflection of terahertz monochromatic surface plasmon-polaritons by a plane mirror

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Abstract. **Using a free electron laser developed in Novosibirsk, we have studied the reflection of monochromatic (λ = 130 μm) surface plasmon-polaritons (SPPs) from a plane mirror attached to a waveguiding surface. It is found that 100 % SPP reflection occurs not only in the perpendicular position of the mirror relative to the surface, but also when the mirror is deflected from the normal by the angle α being smaller than the limiting angle α^* proportional to the SPP wave vector. When the mirror is deflected by the angle greater than α^*, SPPs on a perfectly smooth surface must transform into a bulk wave, while, in the experiment, the SPP reflection coefficient decreases gradually to zero with increasing α, which is a manifestation of dispersion of the wave vector of monochromatic SPPs, caused by their scattering on the inhomogeneities of a real surface.**

Keywords: *terahertz radiation, surface plasmon-polaritons, reflection of evanescent waves, surface electromagnetic waves, Drude model.*

1. Introduction

Currently, the terahertz (THz) range of optical radiation is being intensively explored [1–3]. Along with introscopy, the main directions of the THz technology development include spectroscopy of polymer, organic and biological objects possessing absorption lines in the THz range, which correspond to the rotational and vibrational degrees of freedom of molecules [4], as well as the application of THz radiation in communication networks and devices for the acquisition and processing of information [5, 6].

One of the most effective methods of IR spectroscopy of thin-layer objects and information technologies is the method of surface plasmon-polaritons (SPPs), in which the source radiation is transformed into the evanescent p-polarised wave guided by a conductor surface (metal) with negative dielectric constant [7, 8]. However, a mechanical transfer of SPP spectroscopy methods from the mid-IR range to the THz frequency range turns out impossible due to a number of THz SPP peculiarities: their propagation length reaches thousands of the wavelength λ, the depth of field penetration into the medium (air) amounts to hundreds of λ, the SPP refractive index at the 'metal–air' interface exceeds unity only by 10^{-3}–10^{-4} [9], the contribution of radiation losses to the SPP damping is considerable [10], and THz SPPs are capable of overcoming the centimetre-long gaps between the guiding surfaces [11].

The main obstacles complicating the use of THz SPPs generated by continuous laser radiation are powerful illumination of the photodetector by parasitic bulk waves (BWs) emerging in the process of diffraction of the source radiation on the coupling element, and also in diffraction of the SPPs themselves on the surface bends, and, in addition, by scattering SPPs on the surface inhomogeneities (roughness and foreign inclusions) [12].

Diffraction illumination is a reason of low efficiency of THz time-domain spectroscopy (TDS) when studying THz SPPs [13–15]. A slight difference in phase velocities of harmonic components of broadband SPPs, and also the parasitic BWs from the coupling element and the SPP track, lead to a low resolution of such measurements, which greatly complicates the quantitative estimation of the SPP characteristics and their dispersion.

The most significant results in the study of the THz SPP nature on a flat surface and their peculiarities have been achieved with the use of free electron lasers (FELs) generating intense, smoothly frequency-tunable, monochromatic THz radiation [10, 11, 16, 17]. In particular, the end-fire coupling method has been adapted for the THz frequencies, a cylindrical transformation element capable of effective cut-off of parasitic BWs has been proposed, the field distribution above the track and its dependence on the dielectric coating thickness have been measured, the phenomenon of the THz SPP diffraction on a rectangular edge of the sample has been studied, the THz SPP capability to overcome the centimetre-long gaps between the guiding substrates has been revealed, and also the presence of powerful losses of the THz SPP radiation has been established.

To date, there are many preconditions for the development of plasmonic information-analytical devices (sensors, controllers, interferometers, refractometers, absorption and dispersion spectrometers) and communication lines of the THz range. However, some elements (reflectors, beam splitters, deflectors, focusators, controlled switchers, etc.) of the THz plasmonic communication channels still need to be developed and tested.

This paper presents the results of a study on reflection of monochromatic (λ = 130 μm) THz SPPs by plane mirrors mounted on the surface of a gold sample and oriented perpendicular to the surface. The requirements to the accuracy of the

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Received 8 July 2016; revision received 6 October 2016
Kvantovaya Elektronika **47** (1) 65–70 (2017)
Translated by M.A. Monastyrskiy

mirror installation normally to the surface in order to achieve the 100% SPP reflection are determined. The impact of the surface dielectric coating thickness on the reflection efficiency and the magnitude of permissible deflection of the mirror from the normal is investigated. The possibility of regulating the reflected SPP intensity by the mirror tilt angle to the sample surface is studied.

2. Brief theory

The issue of the SPP reflection from a plane interface between the dielectric media adjacent to the SPP guiding surface has been considered analytically in [18, 19]. Voronko et al. [18] obtained formulas for calculating reflection and transmission coefficients, and also analytical expressions for calculating the radiation patterns of bulk and surface waves generated by SPPs as a result of diffraction at the interface between the media at normal incidence. Vary and Markos [19] studied the SPP passage across the interface of dielectric media not only at normal, but also at oblique incidence. It was found that, at normal incidence, the radiation losses of SPPs caused by their scattering at the barrier can reach 40%, while, at oblique incidence, the transmittance decreases with increasing angle of incidence and vanishes at an angle that is critical for SPPs, whereas the reflection coefficient in this case is less than unity due to partial conversion of SPPs into bulk radiation.

Experimental studies on the reflection of SPPs are complicated by their low propagation length L in the visible range ($L \approx 10\lambda$), but are simply feasible in the IR and THz ranges, where $L \approx 10^3\lambda$. Experiments on the reflection of surface electromagnetic waves (SEWs) from an aluminium foil in the microwave range (λ = 3.55 cm) by a plane mirror were conducted by Bell et al. [20]. It was found that SEWs are reflected from a plane mirror oriented perpendicularly to the sample surface, similar to the case of a plane wave, if the penetration depth of their field into the ambient media exceeds 3λ. We may assume that this statement remains also valid for SEWs (which include SPPs) of the THz range, because the penetration depth of their fields into the air reaches 100λ on a metal uncoated by a dielectric layer.

Note that Bell et al. [20] studied the interaction of SEWs with mirrors, the reflecting face of which is adjacent to the waveguiding surface and set normal to the optical bench. But how high are the requirements to the perpendicularity of the mirror installation to observe 100% reflection of SEWs? What would happen if the mirror is tilted away from the normal? Would this directly result in the SEW transformation into a plane wave? At what angle to the surface such a wave would be emitted into the ambient space? We first consider these issues analytically, and then present the results of test experiments and discuss them.

It is known that the real part k' of the SPP wave vector k is greater than the wave number $k_0 = 2\pi/\lambda$ of a plane wave in the air, which defines the nonradiative nature of SPPs [7, 8]. The ratio $k/k_0 = \kappa$ is called the complex refractive index of the SPP, while the real part $\mathrm{Re}(\kappa) = \kappa'$ is simply the SPP refractive index, since the quotient of the speed of light and κ' is equal to the SPP phase velocity. If any object (edges of a screen or a diffraction grating on the sample surface, irregularities or inhomogeneities on the waveguiding surface, etc.) is located within the SPP field, the SPP wave vector gains an increment $\Delta\boldsymbol{k}$ as a result of the wave diffraction on that object. If the condition

$$|k' - \Delta k'| \leqslant k_0 \tag{1}$$

is fulfilled, where $\Delta k'$ is the real part of Δk, the SPPs are transformed into a plane wave emitted into the ambient medium (typically, air) at a certain angle to the sample surface.

If such an object represents a plane mirror, the reflecting face of which is adjacent to the sample surface and contains a normal, according to the law of conservation of momentum (plasmon-polariton momentum is $p = 2\pi k/h$, where h is the Planck constant), $\Delta k' = 2k'$, the SPPs retain their nature and propagate along the sample in the opposite direction after interaction with the mirror. Placing a mirror at an angle of $\beta \neq 90°$ with respect to the track only leads to a change in the propagation direction of the reflected SPPs.

The process of SPP interaction with a mirror deflected from the normal to the sample surface at an angle α depends on the magnitude of this angle. For convenience of explanation, we may rotate not the mirror, but the sample itself by the angle α (Fig. 1). Let us expand the SPP wave vector into two components relative to the mirror: $k_x = k\cos\alpha$ and $k_y = k\sin\alpha$. At a certain angle α, the equality $k_x = k_0\cos\gamma$ holds true, where γ is the propagation angle of a wave generated by the SPPs as a result of interaction with the mirror. The difference between the angles γ and α is explained by the fact that the y-components of the vectors $\boldsymbol{k}$ and $\boldsymbol{k}_0$ are the same by virtue of the law of conservation of momentum, but the absolute values of these vectors are different ($|k| > |k_0|$). Thus, depending on the magnitude of the angle α, two different outcomes of the SPP interaction with the mirror are possible: at $k_x > k_0\cos\gamma$ the reflected radiation retains the SPP nature, while at $k_x \leqslant k_0\cos\gamma$ the SPP is transformed into a plane wave, which is radiated into the air at a certain angle $\gamma > \alpha$ relative to the normal to the reflecting face of the mirror.

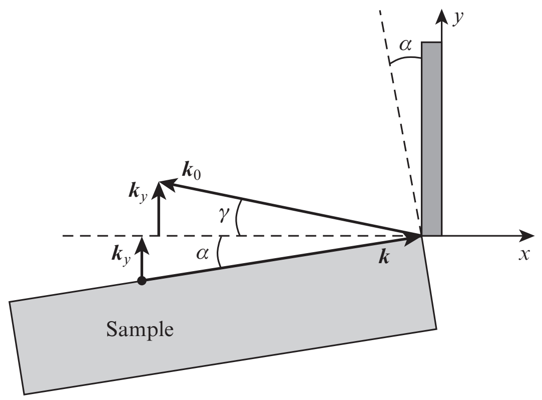

Figure 1. SPP transformation into a plane wave upon SPP reflection by a plane mirror deflected from the normal to the sample surface by the angle α.

We may express the SPP refractive index κ' through the angles α and γ measured at the time moment when the surface wave generates the plane wave. To this end, we make use of the equality of y-component of the vectors $\boldsymbol{k}$ and $\boldsymbol{k}_0$:

$$k_y = k'\sin\alpha = k_0\sin\gamma, \tag{2}$$

whence

$$\kappa' = \frac{\sin\gamma}{\sin\alpha}. \tag{3}$$

In view of the complexity of measuring both angles, we derive an approximate formula for calculating κ' via the value of the angle α at which the beam of monochromatic SPPs incident on the mirror is transformed into a bulk wave. Since the value of κ' in the THz range for the metal–air interface does not exceed 1.001 and the angles α and γ are small, formula (3) implies that the difference between these angles does not exceed 10″, so we can put $\alpha \approx \gamma$. In this approximation, the projection of the SPP wave vector $\boldsymbol{k}$ on the propagation direction of a plane wave generated on the mirror is equal to k_0. Then (see Fig. 1), $k_0/k' \approx \cos 2\alpha$. Hence, we obtain an approximate formula for calculating the maximum angle α_{max} for mirror deflection from the normal, at which the surface monochromatic wave interacting with the mirror is not converted into a plane wave:

$$\alpha_{max} \approx [\arccos(k_0/k')]/2. \qquad (4)$$

3. Experimental setup

The experimental setup is shown in Fig. 2. The beam of p-polarised radiation modulated with a chopper at a frequency of 15 Hz, generated by the Novosibirsk FEL, was directed onto an optical table in the form of a train of 100-ps pulses with a frequency of 5.6 MHz and an average power of ~10 W. In the experiments, we used the radiation with λ = 130 μm having the linewidth of ±1 μm ($\Delta\lambda/\lambda \approx 1\%$).

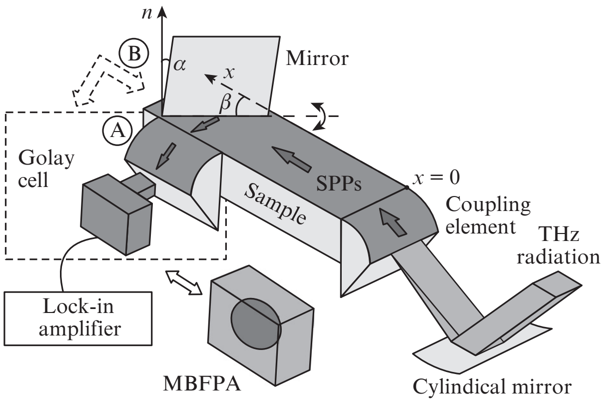

Figure 2. Experimental setup (MBFPA is a microbolometer focal plane array; A, B are MBFPA positions).

To transform the radiation from the FEL into SPPs and back (SPPs into a bulk wave), the end-fire coupling method was applied [21], in which the segments of glass cylinders (R = 60 mm ≫ λ) were used as the matching elements (the 'coupling elements'), with their curved surfaces covered by an opaque layer of gold, on which, in turn, a layer of ZnS with a thickness of 2 μm was applied [17].

Experiments were performed with two sets of samples having different quality of surface preparation: in set No. 1, the glass plates measuring 15.0×3.5×1.0 cm, optically polished faces of which (15.0×3.5 cm) were covered with a 0.3-μm-thick opaque layer of gold, were used as the substrates; set No. 2 was comprised of duralumin parallelepipeds measuring 15.0×3.0×2.0 cm, their faces (15.0×3.0 cm) were polished by cloth and covered with a 1.0-μm-thick layer of gold. The gold coatings of the samples of both sets were covered by a zinc sulphide layer having a thickness up to 2 μm.

The SPPs were reflected using a 40×40 mm plane mirror placed on the waveguiding faces of the sample at its free short rib. The mirror was installed perpendicular to the surface faces in a plane oriented at an angle of β = 45° relative to the SPP track. The mirror possessed two rotation axes: the first coincided with the lower rib of its reflecting face adjacent to the sample, which allowed us to vary the angle α of the mirror tilt relative to the normal to the sample surface; the second axis was directed along the normal to the sample surface, which ensured the possibility of varying the angle α relative to the direction of the SPP propagation. The reflected SPP beam was directed to a cylindrical output element and, at its free rib, was transformed into a bulk wave.

The BW intensity, which is proportional to the SPP intensity, was measured by an opto-acoustic Golay cell connected to a synchronous SR-830 amplifier. For power control of the input FEL beam, a beam splitter and a pyroelectric MG-33 receiver were used. The real-time recording of the BW intensity distribution was performed using an uncooled microbolometer focal plane array (MBFPA). The array manufactured at the Rzhanov Institute of Semiconductor Physics (SB RAS) contains 320×240 bolometers with a size of 51 μm (the total matrix size is 16×12 mm), sensitive to THz radiation, and allows recording of 30 frames per second [22]. The noise equivalent power (NEP) of a single bolometer at λ = 130 μm is about 2×10^{-10} W Hz$^{-1/2}$.

4. Results and discussion

To verify the possibility of the THz SPP reflection by a plane mirror, we have conducted the calculations using the Drude model for the dielectric constant of a metal and the measurements of the depth δ of the SPP field penetration into the air for both sets of samples with the use of a setup described in [17]. The results of these studies are shown in Fig. 3. Firstly, we note good agreement between the results of measurements and calculations, indicating the applicability of the Drude model in the THz range. Secondly (and this is important for the SPP reflection by mirrors), the value of δ for the samples with a ZnS layer having a thickness $d \leqslant 0.5$ μm exceeds 3λ, which corresponds to the condition formulated in [20] for the applicability of the reflection law to SEWs.

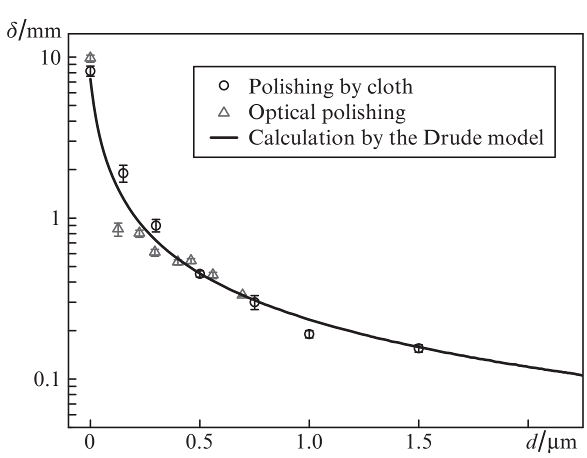

Figure 3. Dependences of the penetration depth δ of the SPP field into the air for the 'Au – ZnS layer of the thickness d – air' structure; the solid curve shows the calculation using the Drude model; circles and triangles – experiment.

To measure the intensity profile of the bulk radiation emerging from the SPP interaction with a plane mirror, we used the MBFPA placed at the sample end in position A (see Fig. 2). Herewith, the second matching element designated to transform the SPP back to the bulk wave was absent. The results of measurements performed with the sample covered by a ZnS layer of thickness 0.15 μm, at normal and tilted positions of the mirror relative to the waveguiding surface, are shown in Fig. 4. It is seen that at $\alpha = 0$, the recorded radiation is concentrated near the surface and corresponds to a typical SPP diffraction pattern on the rectangular end of the sample [17]. At $\alpha = 120' > \alpha_{max}$, in the region where a BW from the reflected plasmon should exist, the intensity is very low, while a maximum is observed far away from the sample plane, which corresponds to a plane wave generated as a result of the SPP interaction with a reflective face of the mirror. These intensity distributions visibly demonstrate that the SPPs retain their nature in the interaction with a mirror oriented perpendicular to the sample surface; in this case, the absence of a bulk wave makes it possible to assert that the SPP reflection coefficient is close to unity. On the other hand, when the mirror is deflected from the surface normal by the angle greater than α_{max}, virtually the entire SPP energy is converted into the energy of a plane wave.

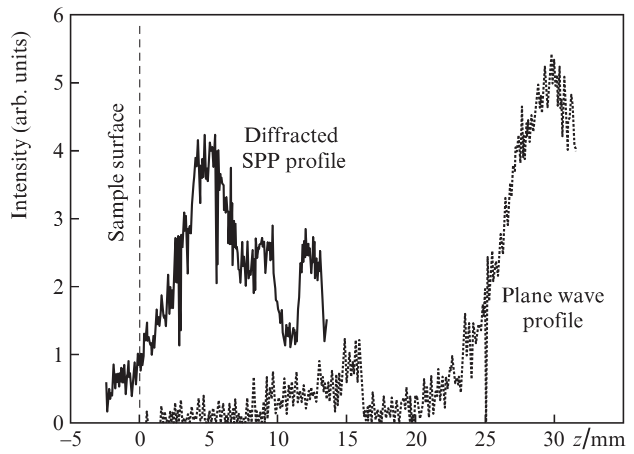

Figure 4. Radiation intensity distribution measured using a microbolometer array (placed at the end of the sample with a 0.15-μm-thick ZnS layer) after the SPP interaction with a plane mirror; solid curve – the mirror is perpendicular to the sample surface ($\alpha = 0$), the dotted curve – $\alpha = 120'$.

The coefficient of SPP reflection from the mirror in its normal orientation to the sample surface ($\alpha = 0$) was determined as follows. To measure the intensity I_{ref} of the reflected SPP, the matching element and the Golay cell were placed in position A (see Fig. 2), while to measure the intensity I_{tr} of the transmitted SPP – in position B (in the latter case the mirror was removed from the sample surface). To ensure identical SPP damping along the sample surface in both measuring schemes, the mirror position along the x axis was chosen so that the distances travelled by the reflected and transmitted SPPs to the corresponding ends of the sample were the same. As a result of measurements, it was found that $I_{ref} \approx I_{tr}$, and hence the SPP reflectivity $R = I_{ref}/I_{tr}$ from the mirror was close to unity. Thus, when the mirror tilt angle $\alpha = 0$, virtually 100% reflection of SPPs takes place.

To measure the dependence of the reflected SPP intensity on the mirror tilt angle α, the cylindrical matching element and the Golay cell were placed in position A. The results of experiments, when the mirror is placed at a distance $x \approx 50$ mm for both sets of samples, are shown in Fig. 5. The axis of ordinates represents the reflectivity $R = I/I_0$, where I_0 is the signal intensity at $\alpha = 0$, which corresponds to 100% SPP reflection. Unfortunately, the working time allocated to FEL users is limited and, at a large amount of work, multiple measurements of relevant dependencis are impossible. According to our estimates, the measurement error of R at a separate point constitutes 10%, which is stipulated mainly by the FEL radiation power instability.

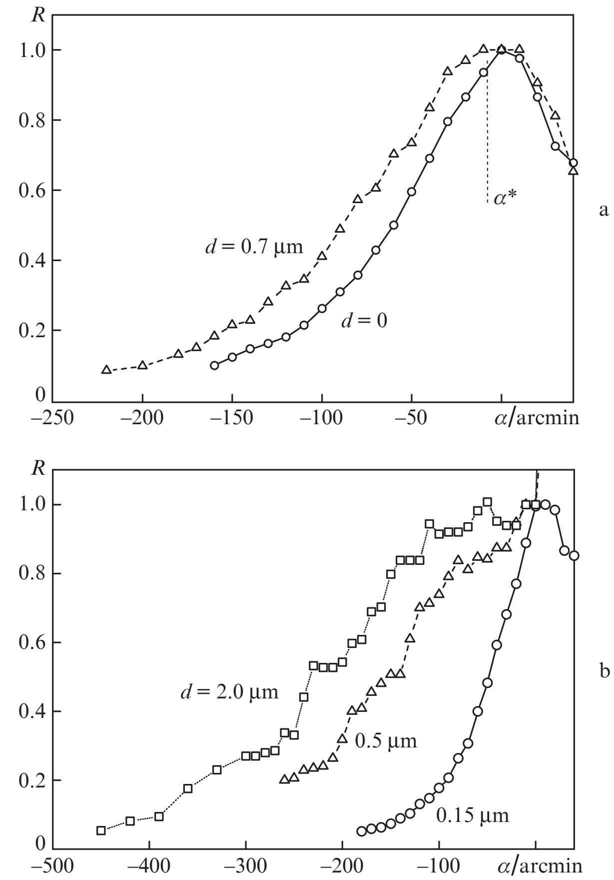

Figure 5. Experimental dependences of the SPP reflection coefficient R on the angle α of the mirror deflection from the normal to the sample surface with a top layer of ZnS of different thickness d for the samples on optically polished glass substrates (a) and the samples on duralumin substrates polished by cloth (b).

Analysis of families of the curves obtained leads to the following conclusions:

– the SPP reflectivity does not drop to zero at a certain angle α_{max} as it follows from formula (4), but decays gradually, which indicates the spread of values of the SPP wave vector (uncertainty of the angle α_{max} caused by 1% linewidth of FEL radiation does not exceed 1′),

– the gradient $\Delta R/\Delta\alpha$ depends on the quality of surface processing: for a set of samples No. 1 with high-quality optical polishing of substrates, the dependences $R(\alpha)$ are much narrower than those for a set of samples No. 2 polished by cloth;

– the dependences $R(\alpha)$ for the samples with a specified quality of surface processing are broadened with increasing coating thickness d, i.e., with increasing SPP wave vector [17];

– in reality, the SPP reflectivity decreases starting from a certain angle $\alpha^* < \alpha_{max}$, the magnitude of which is proportional to the ZnS layer thickness;

– the mirror deflection from the normal in the direction opposite to the direction of the original SPP propagation (positive values of the angle α) leads to the same effects as with the mirror deflection in the direction of the SPP propagation (negative values of angle α), but the recording of the reflected SPPs in this case is complicated by the appearance of bulk radiation (on the mirror) illuminating the array.

We should note several possible practical applications of the THz SPP reflection by plane mirrors. First, the dependence of reflectivity on the mirror tilt angle can be used for the real-time control of the SPP intensity. Second, the dependences of the angular width $R(\alpha)$ and the gradient $\Delta R/\Delta\alpha$ on the substrate surface processing quality allows one to judge about the surface state of optical products.

In addition, a gradual decrease in the reflectivity R with increasing angle α indicates that the SPP wave vector on a real surface is not unambiguous. It has a certain spectrum of values that can be estimated by the formula

$$k' \approx k_0/\cos 2\alpha = k_0/\cos[2(\alpha^* + \Delta\alpha)], \quad (5)$$

where α^* is the maximum mirror tilt angle at which the intensity of reflected SPPs is equal to their intensity at $\alpha = 0$; and $\Delta\alpha$ is an additive to α^* due to the metal surface roughness and presence of inhomogeneities therein. This spectrum width depends on the surface quality: the more inhomogeneities (foreign inclusions, graininess of the metal structure, 'mechanical' roughness) contains the surface, the wider is the SPP wave vector spectrum.

Figure 6 shows the dependences $R(\alpha)$ measured at various lengths x of the SPP path along the sample coated by a ZnS layer with a thickness of 0.45 μm. It is seen that with increasing length of the path x, the dependence becomes flatter. This may indicate that with the SPP propagation on a real surface, the spectrum of the SPP wave vectors broadens due to an increased distance of the wave interaction with inhomogeneities.

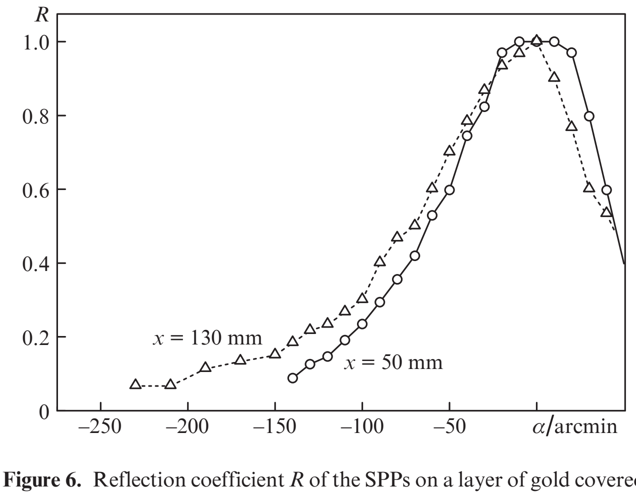

Figure 6. Reflection coefficient R of the SPPs on a layer of gold covered by a layer of ZnS with a thickness of 0.45 μm as a function of angle α of the mirror deflection from the normal to the sample surface, measured at various lengths x of the SPP path.

The measured dependences $R(\alpha)$ allow us to estimate the spectrum of the SPP refractive index κ' (or the real part of the wave vector $\boldsymbol{k}'$). It follows from formula (4) that the SPP refractive index is

$$\kappa' \equiv k'/k_0 \approx 1/\cos 2\alpha_{max}. \quad (6)$$

Now, without regard to any particular waveguiding structure, let us construct the dependence $\kappa'(\alpha_{max})$ (Fig. 7). The region above the curve $\kappa'(\alpha_{max})$ corresponds to the existence of radiation in the form of SPPs reflected by the mirror, while the region below this curve corresponds to a transformation of the incident SPP beam into the BW emitted into the air at an angle lesser than $2\alpha_{max}$. For example, in the 'metal–air' structure ($d = 0$), the SPPs retain their nature in the reflection from a mirror deflected from the normal by an angle lying in the range $0 \leqslant \alpha < \alpha^0_{max} \approx 42'$ (which corresponds to $\kappa' \approx 1.0003$, given the fact that the refractive index of air is 1.00027 [23]). In the presence of a dielectric layer on the metal ($d > 0$), the upper boundary of this range is increased to the value $\alpha_{max} > \alpha^0_{max}$ which is determined by the value of κ' for the SPPs in the 'metal–dielectric layer–air' structure.

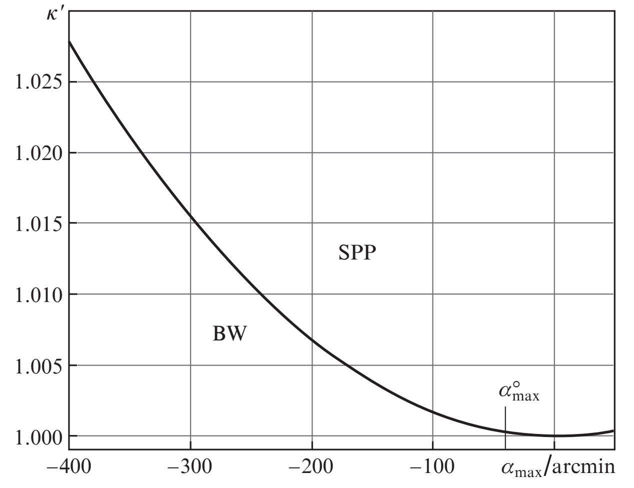

Figure 7. Calculated dependence of the SPP refractive index κ' on the angle α_{max} of the mirror deflection from the normal to the surface, at which the SPP with a given κ' is transformed into a plane wave emitted from the track into the air.

Comparing, in accordance with Fig. 7, each value of the angle α in Fig. 5 with a certain value of κ', one can easily determine the entire range of the κ' values. For example, we can assert that in the samples of set No. 2 (duralumin substrates), the refractive index of the SPP Fourier components was in the range of 1.0003–1.028 (the SPP reflection coefficient for $d = 2.0$ μm was different from zero at $\alpha \leqslant 400'$), whereas in the samples from set No.1 (polished glass substrates), the maximum value of κ' for a sample with $d = 0.7$ μm at $\alpha \leqslant 200'$ only reached 1.007, typical value for the SPPs in the mid-IR range.

It may be assumed that this uncertainty of the wave vector, caused by the SPP scattering on the inhomogeneities of a real surface, is the reason of large radiation losses of SPPs not only in the mid-IR [24, 25], but also in the THz ranges [10].

5. Conclusions

Thus, as a result of our research, it is established that similar to plane waves, surface plasmon-polaritons of the terahertz range are reflected by mirrors. Moreover, the 100% SPP reflection is also retained when the mirror is deflected from the surface normal by a slight angle, which increases with increasing SPP refractive index. At larger mirror deflection angles, the SPP reflection coefficient gradually decreases to zero due to partial conversion of the surface waves into the bulk waves. A smooth decrease in the SPP reflection coefficient depending on the mirror deflection angle indicates that the wave vector of a monochromatic SPP at a real interface is not a strictly defined value, but varies in a certain range which increases with increasing surface inhomogeneity. The reason for such an uncertainty is the SPP scattering by inhomogeneities, leading to the broadening of the Fourier spectrum of the SPP wave vector. We believe that this scatter of the wave vector values is the reason of large radiation losses of THz SPPs.

Acknowledgements. The authors thank the staff of the Siberian Centre for Synchrotron and Terahertz Radiation (Novosibirsk) for the assistance in performing experiments.

This work was supported by the Russian Science Foundation (Grant No. 14-50-00080) and the Russian Foundation for Basic Research (Grant No. 16-32-00678). The work was also performed in the framework of the Programme for Fundamental Scientific Research of the State Academies of Sciences for 2013–2020 (Project No. 0069-2014-0014).

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