In-plane interferometry of terahertz surface plasmon polaritons

A K Nikitin$^{1,2}$, O V Khitrov$^1$, V V Gerasimov$^{2,3}$, I Sh Khasanov$^1$ and T A Ryzhova$^4$

$^1$ Scientific and Technological Centre for Unique Instrumentation of RAS, Butlerova str., 15, Moscow, 117342, Russia
$^2$ Novosibirsk State University, Pirogova str., 1, Novosibirsk, 630090, Russia
$^3$ Budker Institute of Nuclear Physics of the Siberian Branch of the RAS, Acad. Lavrentieva Pr., 11, Novosibirsk, 630090, Russia
$^4$ Peoples Friendship University of Russia, Miklukho-Maklaya str.6, Moscow, 117198, Russia

E-mail: alnikitin@mail.ru

Abstract. The paper is devoted to the development of interferometric schemes for determining the complex refractive index $\kappa = \kappa' + i \cdot \kappa''$ of surface plasmon-polaritons (SPPs) of the terahertz (THz) spectral range. As the value of $\kappa$ depends on the dielectric constant $\varepsilon_m$ of the metal surface guiding the SPPs it can be used for determining $\varepsilon_m$ in the far infrared what other optical methods fail to do due to high reflectivity of metals. We discuss two types of THz SPP interferometers in which the interference pattern is formed as a result of the interaction of SPP beams themselves rather than bulk waves produced by these beams. The first type of interferometers are static devices that enable one to investigate fast processes on the metal surface, while the second type are dynamic ones that make it possible to realize Fourier spectroscopy of the metal surface and its transition layer at THz frequencies. Devices of the both types produce interferograms enabling one to determine the real and the imaginary parts of $\kappa$. The results of experiments on the interaction of THz SPPs with flat mirrors and beam-splitting plates, the key elements of the THz SPP interferometers, are presented.

1. Introduction

Surface plasmon-polaritons (SPPs) representing themselves a complex of an evanescent $p$-polarized electromagnetic wave and a wave of the conduction electrons density onto the surface of a material (usually, metal) with negative real part of its dielectric permittivity are widely used for surface control $[1]$. Being concentrated at the “metal-dielectric” interface SPPs field is very sensitive to the state of the surface and its transition layer. The use of SPPs generated by probing radiation rises up the sensitivity of measurements due to increasing the distance of interaction of radiation with the object and concentration of the field in the near-surface area.

As any EM wave SPPs are characterized by their complex refractive index $\kappa = \kappa' + i \cdot \kappa''$, which determines the measurable characteristics of the SPPs: the propagation length $L = 1/(2k_o \cdot \kappa')$, SPPs field penetration depth $\delta \sim 1/(k_o \cdot \kappa')$ into air, and their phase velocity $v_{ph} = c/\kappa'$ (here $c$ is the speed of light; $k_o = 2\pi/\lambda_o$ ; $\lambda_o$ is radiation wavelength in air) $[2]$. Having measured $L$ (which corresponds to
\( \kappa' \) and \( \theta_{\text{ph}} \) (which corresponds to \( \kappa' \)) one can calculate the permittivity of the metal surface or two unknown parameters (thickness and/or the dielectric constant) of the layer covering the surface.

In the visible range SPPs exhibit to a greater extent the properties of a mechanical wave: their \( \theta_{\text{ph}} \) is much less than the speed of light and it is usually determined without any problems by the angle of incidence of radiation generating SPPs; while the value of \( L \) is only of a few wavelengths and its measurement is problematic.

In the terahertz (THz) region (from 1 to 10 THz), the characteristics of SPPs are very similar to those of a plane wave in free space: their phase velocity \( \theta_{\text{ph}} \) is only slightly less than the speed of light (the difference \( (\kappa'-1) < 10^{-3} \)), while \( L \) amounts to tenths of a meter [3]. This complicates the determination of \( \theta_{\text{ph}} \), but makes the assessment of \( L \) rather easy.

Interferometry is the most reliable and accurate method for determining the phase velocity of plane EM waves. But this statement is not obvious with respect to surface plasmons.

There are two ways of interferometry of surface plasmons: either to register the result of the interaction of bulk waves (BW), one (or both) of which is generated by the SPPs, or to record the interferogram formed by the fields of interacting SPP beams in the near-surface region (the in-plane SPP interferometry). To realize the first way one has to change the distance run by the SPPs during the measurements employing a movable coupling element converting the SPPs into BWs [4]; it is a rather time-consuming procedure and the measurements are characterized by the low signal-to-noise ratio as the SPPs-BWs conversion is accompanied by the generation of strong parasitic waves on the coupling element. The second way of SPP interferometry (the in-plane one) is more promising since it does not need the reverse conversion of SPPs into BWs, and the interferogram can be obtained in both convergent and parallel beams; therefore both static and dynamic SPP interferometers can be built (the first of them can be used for studying fast processes, while the second – for creation of surface-plasmon Fourier spectrometers of the THz range).

2. Interaction of THz SPPs with flat mirrors and beam splitters

To create SPP interferometers, it is necessary to master the operations of reflection and splitting of SPP beams. At first glance, such operations can be performed using Bragg gratings formed on the metal surface [5]. The disadvantages of this method of controlling the SPP beams are not only damage to the surface and the inability to control the influence; its main drawback is that interaction of THz SPP beams with diffraction gratings is accompanied by generation of mighty parasitic near-surface bulk waves, illuminating the photodetector and greatly reducing the signal-to-noise ratio. Geodesic prisms also can split and deflect SPP beams [6], but the drawbacks of Bragg gratings are typical for their use as well.

Possible alternative to the planar elements for controlling the THz SPP beams may be their bulk analogous (flat mirrors and beam-splitting plates), since THz SPPs are very close to plane EM waves in their characteristics (see section 1). Below are the results of our experimental studies on the interaction of flat mirrors and partially transparent plates installed perpendicular to the metal surface with THz SPPs generated by radiation of the Novosibirsk free-electron laser (NovoFEL) [7].

2.1. Reflection of THz SPP beams by flat mirrors

The experimental studies on reflection of THz SPP beams by flat mirrors are fully described in [8]. The SPPs were generated by radiation with the wavelength \( \lambda_0 = 130 \, \mu\text{m} \) having the linewidth of \( \pm 1 \, \mu\text{m} \) (\( \Delta \lambda / \lambda \approx 1\% \)). The samples represented themselves flat glass substrates \( 15 \times 3.5 \times 1.0 \, \text{cm} \) in size with one optically polished face \( (15 \times 3.5, 5 \, \text{cm}) \) coated by a 0.3 \( \mu\text{m} \) thick gold layer obtained with the magnetron sputtering technique and overcoated by a zinc sulphide (ZnS) film of various thickness \( d \). The mirror (glass substrate coated by a layer of gold) was installed perpendicular to the sample face in a plane oriented at an angle of 45\(^\circ\) to the SPP track. To couple the laser radiation and the SPPs we employed the cylindrical element and the end-fire coupling technique [9, 10]. Scheme of the experimental setup is presented in figure 1; here A is the position of the Goley cell used for detection of the reflected beam intensity. The results of measurements for samples with ZnS films of \( d = 0 \) and \( d = 0.7 \, \mu\text{m} \) are plotted in figure 2.
First it should be noted that THz SPPs retain their nature in interaction with a mirror oriented perpendicular to the sample surface provided the gap between the surface and the mirror edge is less than 2\(\alpha\); in this case the SPP reflection coefficient was close to unity. But the greater was the angle of deflection \(\alpha\) of the mirror from the normal to the surface, the more intensive were the stray bulk waves and for \(\alpha \geq 2^\circ\) (this angle limit depends on the surface quality) the reflection coefficient of SPPs tended to zero (see figure 2). Note, that the dependence of reflectivity on the mirror tilt angle \(\alpha\) can be used for the real-time control of the SPP beams intensity. Based on this knowledge we developed and tested the device for measuring the propagation length \(L\) of THz SPPs with a high signal-to-noise ratio due to immobility of the input and output coupling elements [11].

**Figure 1.** The experimental set up (MBFPA is a microbolometer focal plane array; A and B are the MBFPA positions for the reflection and transmission measurements) [8].

**Figure 2.** Measured dependencies of the SPP reflection coefficient \(R\) on the angle \(\alpha\) of the mirror deflection from the normal to the sample surface covered with a ZnS layer of thickness \(d\).

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### 2.2. Splitting THz SPP beams by partially transparent flat plates

To test the possibility of splitting THz SPP beams by means of flat plates we performed measurements similar to the ones described in section 2.1 having replaced the mirror with a partially transparent for THz radiation flat plate [12]. As the material of such a plate we chose a kapton tape with thickness of 125 \(\mu\)m; this choice is explained by the value of kapton refractive index \((n \approx 1.88 + i \cdot 0.02\) [13]) at \(\lambda_n = 130\) \(\mu\)m, which provides low absorption of the radiation and approximately the same values of the reflectance \(R\) and the transmittance \(T\) for a plane THz wave, which is close in its characteristics to the THz SPPs. When measuring \(T\) the Golay detector was placed in position B (figure 1).

As a result of the measurements it was found [12] that: 1) THz SPPs are reflected and transmitted by the kapton plate about to the same extent as a plane wave of the same frequency is; 2) the values of \(R\) and \(T\) for the SPPs, equal to \(R = 0.28 \pm 0.03\) and \(T = 0.45 \pm 0.05\) at the incidence angle \(\beta = 45^\circ\), depend on this angle rather slightly (gradually decreasing and rising with increasing the angle, respectively); 3) the sum of \(R\) and \(T\) is noticeably less that unity (namely: \(R + T \approx 0.8\)), that can be explained not only by the absorption of radiation inside the plate, but also by the diffraction losses of the SPPs due to the loose adhesion of the plate to the sample surface and as a result of the SPP passing through of the impedance barrier [14], which is constituted by the plate; 4) the thicker is the dielectric (ZnS) film covering the surface of the metal the less is transmittance of the SPPs.

Summing up the results of the experiments, it can be stated that rigid kapton plates of submillimeter thickness can be effectively used for splitting beams of THz SPPs. However, it should be noted, that splitting of THz SPP beams by means of such plates is accompanied by the generation of parasitic bulk waves due to the diffraction of the SPPs on the plate edge. Nevertheless, the intensity of these parasitic waves and the energy losses of the SPPs are significantly less than those occurring on planar diffraction gratings used for the splitting of THz SPP beams.
3. Static two-beam surface plasmon interferometer of the terahertz range

3.1. Chronology of the development of SPP static interferometry

A number of papers on SPP static interferometry have been published. The earliest of them is [15]. The technique is based on the effect of dramatic change of the phase of radiation generating the SPPs by the method of attenuated total internal reflection (ATR). Later on the idea was picked up by other scientists (e.g. [16, 17]). However, the technique is not applicable in the infrared (IR) and THz ranges due to the macroscopic propagation length of SPPs much exceeding the radiation beam diameter.

A new step in the development of the static SPP interferometry theme is associated with the use of a broadband light source illuminating a slit (or a couple of slits) in an opaque metal layer to generate SPPs propagating normal to the slit(s); on running some distance the SPPs are reflected from a groove parallel to the slit and return to it where they produce bulk radiation interfering with the incident light; the formed interference pattern is analyzed by a spectrometer [18]. Such SPP-interferometers are used mainly for sensor applications and they operate only in the visible or near IR range [19-21].

The first scheme of a static THz SPP interferometer based on the use of flat mirrors was suggested in [22]. On the basis of the scheme, the theory of dispersion Fourier transform infrared SPP-spectroscopy was developed [23]. However experiments to test such interferometers were not carried out due to insufficient knowledge at that time about the interaction of THz SPPs with flat mirrors. Moreover, the operation of such an interferometer could be characterized by a low signal to noise ratio due to diffraction of the SPPs at the edge of the angular mirror splitting the original beam.

3.2. Schematic of the static THz SPP interferometer and its description

Our objective was to simplify both the scheme of the known interferometer for determining the complex refractive index of THz SPPs [22], and the procedure for processing the measurement results.

Simplification of the interferometer scheme is achieved by excluding two angular and three flat mirrors from it. In the new scheme, the splitting of the initial SPP beam into two new ones is realized not by an angular mirror, but by a translucent plane-parallel plate mounted on the waveguiding surface and oriented perpendicular to it and to the SPP track.

Simplification of the procedure for processing the results of measurements is a consequence of the possibility of calculating the imaginary part $\kappa''$ of the SPPs’ refractive index with respect to the intensity distribution on the photodetector array of each of the interfering beams separately (measured while blocking the other beam with by a flap introduced into the scheme), which makes it possible not only to obtain the calculation formula in an explicit form, but also apply it repeatedly to different points of the interferogram in order to improve the accuracy of $\kappa''$ determination.

Figure 3 shows the schematic (top view) of the elaborated device, where the numerals denote: (1) is a source of collimated $p$-polarized (relatively to the SPP guiding surface) monochromatic IR or THz radiation; (2) is an element for coupling the source radiation and the SPPs; (3) is a flat facet of the sample, capable of guiding the SPPs; (4) is a semitransparent flat-parallel plate, oriented at an angle $\gamma$ with respect to the SPP beam incident on it, and characterized by the coefficient of reflection $R$ and the coefficient of transmittance $T$ as applied to the SPPs; (5) is a plane mirror oriented at an angle $\beta < \gamma$ with respect to the SPP beam incident on it; (6) is a photodetector array adjacent to the facet 3; (7) is an information processing device; (8) is a rotational shutter, allowing to shut alternately the interfering SPP beams. Element (2) represents itself a cylindrical segment with the radius of curvature $r >> \lambda$ and sharp edges of the curved surface. Such form of the coupling element makes it possible not only to use the end-fire coupling method [10], but also to shield effectively the receiver from parasitic exposures [9]. Note that the reflection coefficient of SPPs depends on the angle of deviation of mirror (5) or plate (4) from the normal to the waveguiding surface [8]; this makes it possible to achieve the desired contrast of the interference pattern when tuning the device.

The interferometer works as follows. Radiation (with the wavelength $\lambda_s$) from source (1) is directed onto element (2), which converts the bulk radiation into the SPPs. The collimated beam of SPPs propagates along the sample facet (3) and falls on plate (4), which splits the original beam into
two secondary ones [12]. The beam, passed through plate 4, falls onto mirror 5 and is reflected by it to

\[ \kappa' = \frac{m \cdot \lambda}{\Delta S_j - \Delta S_{j+m}} \]  

Figure 3. Schematic of the static THz SPP interferometer.

photodetector array (6), where it interacts with the other secondary beam reflected by plate (4). As a result of the interaction of the beams, the interferogram recorded by array (6) is formed. Electric signals from the pixels of array (6) are fed to device (7) which, employing values of the signals in two maxima of the interferogram and the pixel coordinates, calculates the real part \( \kappa' \) of the SPPs refractive index:

\[ (S_1)_j = l_j + (S_{12})_j = l_j \left( 1 + \frac{1}{\cos(2\beta)} \right), \]

\[ (S_2)_j = h_j + (S_{22})_j = h_j \left( 1 + \frac{1}{\cos(2\gamma)} \right), \]

here: \( l_j = l_o + \Delta l_j = l_o + x_j \cdot \tan(\beta) \) and \( h_j = h_o + \Delta h_j = h_o + x_j \cdot \tan(\gamma) \) are the distances travelled by the \( j \)-th ray from element (2) to mirror (5) and plate (4), respectively; \( l_o \) and \( h_o \) are the smallest distances separating mirror (5) and plate (4) from element (2), respectively; \( x_j \) is the abscissa of the
$j$-th ray of the SPP beam on element (2), calculated by the formula: $x_j = x_{int} \cdot \cos(2\beta) - l_o \cdot \sin(2\beta)$, here $x_{int}$ is the coordinate of the same ray on array (6).

Note that formula (1) can be applied many times (for different combinations of $j$ and $(j+m)$ maxima) in processing of this interferogram in order to find the mean value of $\kappa'$ and to increase the accuracy of its determination.

Value of the imaginary part $\kappa''$ of the SPP refractive index can also be determined from the interferogram by solving the nonlinear equation that describes the dependence of the resulting intensity on the coordinate $x$ with respect to $\kappa''$ [22]. But we offer an instrument solution to this problem, which makes it easier to process the results of measurements; it implies measuring the intensity distributions $I_1(x)$ and $I_2(x)$ on photodetector array (6) of each of the interfering beams individually, closing the other beam with shutter (8). Then, knowing the pixels abscissas $x_{int}$ of array (6) and intensities of the beams $I_1, I_2$ on the pixels, the value of $\kappa''$ can be calculated by the formula:

$$
\kappa'' = \frac{\ln \left[ \frac{T \cdot I_2(x_{int})}{R \cdot I_1(x_{int})} \right]}{2k_o \cdot (l-h) + \frac{l}{\cos(2\beta)} - \frac{h}{\cos(2\gamma)}}
$$

here: $l = l_o + x \cdot \tan(\beta)$, $h = h_o + x \cdot \tan(\gamma)$, $x = x_{int} \cdot \cos(2\beta) - l_o \cdot \sin(2\beta)$.

As in the case of determining $\kappa'$, multiple determination of $\kappa''$ contributes to an increase in the accuracy of its sought mean value. We should note that the method described for determining $\kappa''$ actually reproduces the known "two-prism" technique for determining the propagation length of SPPs, in which the natural logarithm of the ratio of the intensities of SPPs that have traveled different distances is related to the difference of these distances [2].

3.3. Numerical modeling

To illustrate the operation of the interferometer, let us consider the possibility of determining the refractive index of SPPs generated by radiation with $\lambda_o = 130 \text{ µm}$ on a flat surface of a gold sample (100×50 mm$^2$) disposed in vacuum and containing 0.5 µm thick ZnS coating. As beam splitter (4) let's take a kapton plate characterized with $R = 0.28$ and $T = 0.45$. The width of the radiation beam is set equal to 10 mm, the distances $l_o = 80 \text{ mm}$, $h_o = 50 \text{ mm}$, $x_o = 30 \text{ mm}$. In order for interfering beams of SPPs could intersect on array (6), with the chosen values of $l_o$, $h_o$ and $x_o$, the angles $\beta$ and $\gamma$ should equal $10^\circ17'$ and $15^\circ29'$, respectively. Recording of the interferogram can be performed by an array of microbolometers (containing 320 pixels 51 µm each) with its total length of 16.32 mm [24].

Figure 4 shows the interferograms recorded in this case on array (6) for different distances $h_o$ spacing the splitting plate (4) from the coupling element (2) under the condition of equal radiation intensity along the cross section of the SPP beam. Note the larger is $h_o$ the greater is the interference pattern period, the higher is the accuracy of $\kappa'$ determination.

To calculate $\kappa'$, let us consider the 1-st and 17-th maxima of the pattern depicted in figure 4 (a); on array (6) they have coordinates $x_{int} = 30.41 \text{ mm}$ and $x_{17int} = 40.23 \text{ mm}$, respectively. On substituting the values $l_o, h_o, x_o, \lambda, \beta, \gamma, x_{int}, x_{17int}$ in (1) and setting $m = 16$, we get: $\kappa' = 1.00053$.

To determine $\kappa''$ let us select on the interferogram the pixel of array 6 with the abscissa $x_{int} = 36.0 \text{ mm}$. By shutting alternately the interfering SPP beams with gate (8), we establish that at this point the relative intensities of the beams $I_1/I_o = 0.0322$ and $I_2/I_o = 0.0205$ ($I_o$ is the intensity of the SPP beam at the output of element (2). Then, substituting in (2) the values $l_o, h_o, x_o, \lambda, \beta, \gamma, k_{refl}, k_{trans}, x_{int}, I_1/I_o$ and $I_2/I_o$, we get: $\kappa'' = 0.000024$. 

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Figure 4. Interference pattern recorded by the SPP interferometer photodetector array 6 for different distances \( h_0 \) spacing the splitting plate 4 and the coupling element 2: (a) \( h_0 = 50 \) mm; (b) \( h_0 = 70 \) mm.

Thus, the static interferometer enables one to determine the refractive index of THz SPPs almost instantaneously, which is extremely important for studying fast processes on conducting surfaces.

4. Dynamic surface plasmon interferometer of the terahertz range

4.1. Schematic of the dynamic THz SPP interferometer and its description

The chance of using flat mirrors and beam splitters for reflecting and dividing beams of THz SPPs makes it possible to develop the scheme of a dynamic SPP interferometer, similar to the scheme of the Michelson interferometer for three-dimensional waves.

Figure 5 shows the schematic (top view) of the elaborated THz SPP interferometer, where the numerals denote: (1) is a source of collimated \( p \)-polarized THz radiation; (2) is an element for coupling the radiation and the SPPs; (3) is a flat facet of the sample capable of guiding the SPPs; (4) is a partially transparent flat-parallel plate oriented at 45° to the incident SPP beam and characterized by the coefficient of reflection \( R \) and the coefficient of transmittance \( T \) as applied to the SPPs; (5) is an immobile plane mirror oriented normally to the SPP beam reflected by plate (4); (6) is one more mirror, which is oriented normally to the SPP beam transmitted through plate (4) and capable of moving along this beam track; (7) is a single-pixel photodetector; (8) is an information storage and processing device.

Figure 5. Schematic of the dynamic THz SPP interferometer.
The interferometer works as follows. Radiation from source (1) is directed onto element (2), which converts it into the SPPs. The collimated beam of SPPs propagates along the sample facet (3) and falls on plate (4), which splits the original beam into two secondary ones [12]. The beam reflected by plate (4) is reflected from mirror (5) and propagates in the opposite direction [8]. The beam, passed through splitter (4), reaches mirror (6), is reflected from it and returns to splitter (4). The first of the secondary beams partially passes through the plate (4), while the second is partially reflected by it. Having interacted with splitter (4) both secondary beams propagate along the same track (perpendicular to the plane of incidence), reach the edge of the sample facet (3) and, as a result of diffraction on the edge, are converted into bulk waves [25], the intensities of which are proportional to the intensity of the secondary SPP beams. The bulk waves interfere with each other and illuminate photo detector (7). The signal generated by it enters device (8), which stores the value of the signal I and the corresponding coordinate x of mirror (6). Further, mirror (6) is shifted along the x-axis by one "step" Δx and device (8) registers a new couple of values of the signal I and the coordinate x = x₀ ± Δx (here x₀ is the initial coordinate of the mirror) corresponding to the new position of mirror (6). The procedure of such measurements continues until mirror (6) is shifted to the maximum distance xₘₐₓ from its initial position. The obtained dependence Iₖₒₜₜ (x) is the desired interferogram and it is described by the expression:

\[
I_{i, o}(x) = I_o \cdot R \cdot T \cdot \left[ e^{-\alpha(2b + a)} + e^{-\alpha(2x + a)} + 2 \cdot \sqrt{e^{-2\alpha(b + x + a)}} \cdot \cos(\Delta \phi) \right],
\]  

here Iₒ is the intensity of the SPP beam incident on splitter (4); \( \alpha = 2k_o \cdot \kappa'' \) is the attenuation factor of the SPPs; \( b \) is the distance from splitter (4) to mirror (5); \( a \) is the distance from splitter (4) to the edge of facet (3); \( x \) is the distance from splitter (4) to the current position of mirror (6); \( \Delta \phi = k_o \cdot \kappa' \cdot |x_o - x| \) is the phase shift gained by the SPPs on the increment \( |x_o - x| \) of the distance spacing splitter (4) and mirror (6).

The interferogram enables one to determine both parts of the refractive index \( \kappa = \kappa' + i \cdot \kappa'' \) of SPPs. The real part of \( \kappa \) can be estimated by relating the wavelength of radiation in air to the wavelength of the SPPs: \( \kappa' = \frac{\lambda_o}{\lambda_{SP}} \). To determine the SPP-wavelength (\( \lambda_{SP} \)), one has to divide the double displacement (the change of the distance, run by the SPP-beam) of the movable mirror \( \Delta l = 2 |x - x_o| \) providing monitoring \( m \) maxima of the interferogram by the number of these maxima: \( \lambda_{SP} = \Delta l / m \).

Thus, the final formula for calculating \( \kappa' \) has the form:

\[
\kappa' = \frac{m \cdot \lambda_o}{\Delta l} = \frac{m \cdot \lambda_o}{2 |x - x_o|}.
\]

Note that the accuracy of the definition of \( \kappa' \) is proportional to the number of periods \( m \) considered.

As in the case of the static SPP interferometer, the value of \( \kappa'' \) can be determined from the interferogram as well. But we again suggest an instrument solution to this problem, which consists in measuring the dependence of the intensity of the secondary beam \( I(x) \) passing through splitter (4), sequentially reflected by mirror (6) and by splitter (4) in the absence of mirror (5) onto the facet (3). In this case, for any values \( I_1 \) and \( I_2 \) measured at the mirror (6) positions with coordinates \( x_1 \) and \( x_2 \) (where \( x_1 > x_2 \)), respectively, the following ratio is true:

\[
\alpha = \frac{\ln \left( \frac{I_2}{I_1} \right)}{2(x_1 - x_2)},
\]

Equating the right part of expression (5) to the definition formula for \( \alpha = 2k_o \cdot \kappa'' \), we obtain:

\[
\kappa'' = \frac{\ln \left( \frac{I_2}{I_1} \right)}{4k_o \cdot (x_1 - x_2)}.
\]
Multiple calculation of $\kappa''$ value for different coordinates $x_1$ and $x_2$, in order to find the average value of $\kappa''$, improves the accuracy of its determination. Note that the described technique of determining the true value of $\kappa''$ actually reproduces the known "two-prism" technique for determining the propagation length of infrared SPPs [26, 2].

The increase in the accuracy of determining both parts the complex refractive by the dynamic SPP interferometer is achieved as a result of: 1) the application of the series method in assessing the value of the interferogram period by recording a greater number of periods compared to the static device due to a greater change in the path difference of the interfering beams in the measurement process; 2) the use of a single-pixel (instead of a multi-pixel) photodetector device characterized by a greater aperture and sensitivity than individual pixels of a photodetector array.

4.2. Computer simulations

As an example, let us consider operation of the dynamic interferometer in which the interferogram is formed by SPPs generated by radiation with $\lambda_0 = 130$ µm on the flat face of a gold sample disposed in air and containing 0.5 µm thick ZnS coverage. Let the distances $a$, $b$ and $x_0$ be the same and equal to 2.0 cm; as the SPP-beam splitting device let us choose the kapton plate (see section 2.2) with $R = 0.28$ and $T = 0.45$. Assuming $I_0 = 1$, $\Delta x = 1.0$ mm, $x_0 = 0$, $x_{\text{max}} = 1.0$ cm and substituting the values for $\kappa'$ and $\kappa''$ found in Section 3.3 ($\kappa' = 1.00053$; $\kappa'' = 0.000024$) into the expression (3), the interference pattern for the was calculated. A fragment of it is presented in figure 6. It turned out that the distance $x_{\text{max}}$ fit a little more than 153 full periods of the pattern; more precisely, $m = 153$ full periods fit the distance of $(x - x_0)$ = 9.94 mm. Substituting values of $m$, $(x - x_0)$ and $\lambda_0$ into formula (4) we get the value of $\kappa' = 1.00051 \pm 3 \cdot 10^{-5}$. Note that such a high accuracy of $\kappa'$ definition is determined not so much by the size of mirror (6) displacement "step" as by the number $m$ of recorded maxima.

![Interferogram](image.png)

**Figure 6.** Fragment of the calculated interferogram for the dynamic SPP-interferometer.

For determining the value of $\kappa''$ one has to measure the dependence $I(x - x_0)$ obtained for the secondary beam interacting with mirror (6) in the absence of mirror (5). Using the data of measurements and applying formula (6) for many pairs of the coordinate $x$, one can obtained the average value of $\kappa''$. We should note that for a more accurate determination of the attenuation of THz SPPs, it is desirable to choose the maximum displacement of mirror (6) comparable to the propagation length of the SPPs, so that the changes in the intensity of the SPP beam could be measured confidently.

The dynamic SPP-interferometer can be effectively used not only in optical sensing and refractometry of metal surfaces, but also in surface plasmon Fourier spectrometers employing such broadband THz radiation sources as synchrotrons or pulsed lasers.
5. Summary
It has been established that surface plasmon-polaritons (SPPs) of the terahertz (THz) range are reflected by flat mirrors and split by partially transparent flat plates like plane EM waves provided their field penetration depth into air exceeds two wavelengths of the radiation and the mirror or the plate adhere to the surface being oriented along the normal to it. Two types of THz SPP interferometers in which interferograms are formed by the fields of the surface plasmons themselves, rather than by the bulk waves generated by them, are considered: the static and the dynamic ones. The first of these enable one to determine the refractive index of THz SPPs almost instantaneously, which is extremely important for sensing fast processes on conducting surfaces; the second of them are more precise (though require a longer time interval for measurements) and may be the key element for future surface plasmon Fourier spectrometers of the THz range.

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