Quality control of solid surfaces by the method of surface plasmon interferometry in the terahertz range

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Abstract. The article considers the possibility of controlling the quality of a conducting surface using a Michelson interferometer, in which the information carrier is surface plasmon-polaritons (a type of surface electromagnetic waves) of the terahertz range. It is shown that using such an interferometer, it is possible both to control the uniformity of the dielectric coating on the surface of a metal product, and to detect inhomogeneities on the controlled surface, as well as to evaluate their geometric and optical characteristics.

Surface plasmon-polaritons (SPPs), abbreviated as surface plasmons, which are a type of surface electromagnetic waves widely used in absorption spectroscopy of thin layers on conductive substrates and in metal products surfaces control [1]. The reason for this is high sensitivity of SPPs to the properties of the surface and its transition layer due to the concentration of the SPP field in the near-surface area. The measurable characteristic of SPPs in the infrared and terahertz (THz) ranges is their propagation length $L$, which is inversely proportional to the imaginary part of the SPP refractive index $\kappa' = \kappa' + i \cdot \kappa''$ and reaching (under real conditions) decimeters at THz frequencies [2].

No less informative is the real part $\kappa'$ of the refractive index of SPPs, which determines the phase velocity $\varphi_{\text{pp}}$ of the wave; however, its measurement is complicated by the proximity of $\varphi_{\text{pp}}$ to the speed of light. Such measurements could be performed by interferometry, but are not so far implemented due to the high level of noise created by parasitic bulk waves (BW) produced when splitting a plasmon beam with a corner mirror [3]. Recently, it has been proposed to use a polyimide (Kapton) film for splitting THz surface plasmon beams [4]. The intensity of parasitic BWs occurring in this way of splitting is significantly lower than when using a corner mirror. This fact makes it possible to create THz plasmon interferometers, in which the interference pattern is formed not by bulk waves generated by the SPPs, but by the SPP beams themselves. The obtained interferograms enable one to determine both parts of the complex refractive index of THz SPPs: $\kappa'$ – by the period of the interferogram, $\kappa''$ – by the change in its contrast.

In this paper, we will study the possibility of detecting and evaluating inhomogeneities on a flat surface of a metal product using the Michelson THz surface plasmon interferometer, in which transparent plates and flat mirrors are used for splitting and reflecting collimated beams of monochromatic THz SPPs.
1. Surface plasmon Michelson interferometer of the terahertz range

1.1. Schematic of the interferometer assembled on a homogeneous flat substrate

At THz frequencies (from 1 to 10 THz, which corresponds to the wavelengths $\lambda$ from 300 to 30 $\mu$m), the estimated propagation length $L$ of SPPs (the distance at which the wave intensity decreases in $e^{\approx 2.718}$ times) reaches meters ($\sim 10^4\lambda$) [3, 4]. Meanwhile, on real metal surfaces containing roughness and heterogeneities, the value of $L$ is an order of magnitude smaller than the calculated one since, along with the Joule losses, SPPs also have radiation losses due to partial transformation of the SPPs into bulk radiation emitted from their track into the environment [5]. But still, decimeters $L$-values are sufficient to control flat faces of most metal products using THz SPPs.

Figure 1. Schematic of the surface plasmon Michelson interferometer of the THz range:
1 – a source of monochromatic THz radiation; 2 – an element for coupling the radiation and the SPPs; 3 – a flat metal substrate; 4 – a plane beam-splitting plate (splitter); 5 – a fixed plane mirror; 6 – a movable plane mirror; 7 – a photodetector; 8 – a computer.

Figure 1 shows the schematic of the elaborated Michelson SPP interferometer, which can be used for specific quality control of metal products flat faces. The interferometer works as follows. Monochromatic THz radiation from source 1 is transmitted to element 2, which converts it into SPPs. The collimated SPP beam propagates along the flat face 3 of the sample and reaches the plate 4, which splits the original SPP beam into two secondary ones [4]. The beam reflected by plate 4 reaches mirror 5, interacts with it [6], and goes back to splitter 4. The beam that passes through plate 4 is reflected from mirror 6 and returns to splitter 4 as well. The first of the secondary beams partially passes through plate 4, while the second one is partially reflected from it. From splitter 4, both secondary beams propagate along the same trajectory (perpendicular to the plane of incidence), interact with each other, and illuminate photodetector 7. The signal generated by it is sent to device 8, which stores the value $I$ of the signal and the corresponding $x$-coordinate of mirror 6. Then this mirror is shifted along the $x$-axis by a step $\Delta x$ and device 8 registers a new pair of values of the signal $I$ and the coordinate $x = x_0 \pm \Delta x$ (here $x_0$ is the initial coordinate of mirror 6) corresponding to the new position of the mirror. The procedure for such measurements continues until mirror 6 is shifted to the maximum distance $\Delta x_m$ from its initial position. The resulting dependence $I_{\text{int}}(x)$ that is the desired interferogram is described by the expression:

$$I_{\text{int}}(x) = I_o \cdot R \cdot T \cdot \left( \exp[-\alpha \cdot (2b + a)] + \exp[-\alpha \cdot (2x + a)] + 2 \cdot \sqrt{\exp[-2\alpha \cdot (b + x + a)]} \cdot \cos(\Delta \phi) \right), \quad (1)$$

here $I_o$ is the intensity of the original SPP beam incident on splitter 4; $R$ and $T$ are the reflectance and transmittance of splitter 4, respectively; $\alpha = 2k_o \cdot \kappa''$ is the damping factor of the SPPs; $b$ is the
distance from splitter 4 to mirror 5; \(a\) is the distance from splitter 4 to photodetector 7; \(x\) is the distance from splitter 4 to the current position of mirror 6; \(\Delta \varphi = 2k_o \cdot \kappa' \cdot |x_o - x|\) is the phase change of the SPPs, which have run there and back the distance \(|x_o - x|\) in the “shoulder” with mirror 6; \(k_o = 2\pi/\lambda\).

Since \(\kappa' = \lambda/L_{\text{SPP}}\) (here \(\lambda_{\text{SPP}}\) is the SPP wavelength equal to twice the period \(\Lambda\) of the interference pattern), the interferogram can be used to determine the real part of the refractive index of the SPPs:

\[
\kappa' = \frac{m \cdot \Lambda}{\Delta x_m} = \frac{m \cdot \lambda}{2 \cdot \Delta x_m},
\]

where \(m\) is the number of maxima on the interferogram when mirror 6 is shifted by a distance \(\Delta x_m\).

The interferogram also contains information about the imaginary part \(\kappa''\) of the refractive index of the SPPs. However, with a small attenuation of THz SPPs and short \(\Delta x_m\), the accuracy of determining \(\kappa'' = 1/(2k_o \cdot L)\) by the change of the pattern contrast is low. Therefore, we proposed to measure \(L\) (which is equivalent to determination of \(\kappa''\)) using a simplified setup sketched in Figure 1. To do this, one has to repeat the above-described measurement procedure having removed mirror 5 from the controlled facet 3 of the sample. In this case, device 8 will accumulate a set of pairs of signal intensity values \(I\) and the corresponding \(x\)-coordinates of mirror 6. Based on the results of measurements at any two points of the SPP track that are separated by a distance \(\Delta x = x_1 - x_2\) (where \(x_1 > x_2\)), it is possible to calculate the SPP propagation length [1]: \(L = \Delta x/\ln(I_1/I_2)\). Given that in the interferometer under consideration, the displacement of mirror 6 by a distance \(\Delta x\) leads to a change in the distance of the SPP run by the amount \(2 \cdot \Delta x\), we can write:

\[
\kappa'' = \frac{\ln(I_1/I_2)}{2k_o \cdot 2 \Delta x} = \frac{\ln(I_1/I_2)}{4k_o \cdot (x_1 - x_2)}.
\]

It should be noted that the integral nature of recording the resulting intensity of the interfering SPP beams, as well as the multiplicity of measurements and subsequent averaging of the calculation results, contributes to improving the accuracy of determining both \(\kappa'\) and \(\kappa''\) using the interferometer.

### 1.2. Numerical simulations of the SPP interferogram

Consider the operation of the interferometer on the example of SPPs generated by radiation with \(\lambda = 130\ \mu m\) on a flat "Au – 1.0 \(\mu m\) ZnS layer – Vacuum" structure. In order to plot an interferogram described by expression (1) for SPPs in the structure, we calculated their complex refractive index \(\kappa = \kappa' + i \cdot \kappa''\) using the dispersion equation for SPPs in a three-layer system [1]. The dielectric permittivity of gold was found using the Drude model, substituting values of the collision frequency of the conduction electrons \(\omega_c = 215\ \text{cm}^{-1}\) and the plasma frequency \(\omega_p = 72800\ \text{cm}^{-1}\) [7], while the refractive index of zinc sulphide was put equal to \(n_{\text{ZnS}} = 2.95 + i0.01\) [8]. The distances \(a, b\) and \(x_0\) were chosen the same and equal to \(3.0\ \text{cm}\), \(I_o = 1\), \(\Delta x = 1\ \mu m\), \(\Delta x_m = 1.0\ \text{cm}\), and as a beam splitter 4 (see figure 1) a Kapton plate characterized by coefficients \(R = 0.28\) and \(T = 0.45\) [4] was taken.

Figure 2 shows two fragments of the calculated interferogram corresponding to the two extreme one-millimetre offset intervals of mirror 6: (a) from \(x = x_0\) to \(x = 2.9\ \text{mm}\); (b) from \(x = 2.1\ \text{mm}\) to \(x = 2.0\ \text{mm}\). One can see that the period of the pattern does not change with the variation in the position of mirror 6, and its contrast gradually increases as the distance run by the SPPs from mirror 6 to the beam-splitter 4 shortens. In accordance with the series method, recording a large number of interferogram periods can improve the accuracy of determining the \(\kappa'\)-value by a factor of \(\sqrt{N}\) (where \(N\) is the number of periods on the pattern). So, in this example, at the step \(\Delta x = 1\ \mu m\) of mirror 6 offset, the relative error of determining \(\Lambda\) is approximately 1%, and the number of registered periods \(N = 152\); therefore, the accuracy of determining \(\kappa'\) is approximately \(5 \cdot 10^{-4}\), which is sufficient to determine the thickness \(d_{\text{ZnS}}\) of the zinc sulphide layer with an accuracy of 0.1 \(\mu m\) (see figure 3a).
Figure 2. The extreme fragments of the SPP pattern calculated for the structure "*Au* – 1.0 µm *ZnS* layer – *Vacuum*" when moving mirror 6 of the Michelson surface plasmon interferometer from the position \(x_0=3.0\) cm to \(x=2.0\) cm: (a) from \(x=x_0\) to \(x=2.9\) mm; (b) from \(x=2.1\) mm to \(x=2.0\) mm.

Figure 3. Calculated dependences of the real part \(\kappa'\) of the refractive index (a) and the wavelength \(\lambda_{SPP}\) of the SPPs (b) generated by radiation with \(\lambda=130\) µm in the structure "*Au* – *ZnS* layer – *Vacuum*" on the *ZnS* layer thickness \(d_{ZnS}\).

Figure 3 shows the calculated dependencies \(\kappa'(d_{ZnS})\) и \(\lambda_{SPP}(d_{ZnS})=\lambda/\kappa'\) for the structure under consideration. It can be seen that both curves are nonlinear and substantiate the high sensitivity of the phase velocity and the wavelength of the SPPs to changes in the thickness of *ZnS* coating of the gold substrate. This indicates that the THz SPP interferometry method can be effectively used to control the thickness of the dielectric coating of metal products.
2. Application of the surface plasmon interferometer for detecting inhomogeneities on flat faces of metal products

2.1. Schematic of the measuring setup
Figure 4 shows the schematic of a defectoscope, the key element of which is the Michelson surface plasmon interferometer of the THz range considered above. To use the defectoscope, it is necessary that the interferometer substrate and the controlled surface of the product are made of the same material, are in the same plane, and their side faces are interfaced and can move relative to each other along the plane of incidence of radiation in the interferometer. In this case, the fixed mirror of the interferometer is placed above the controlled facet of the product within the field of the SPPs. The work of the defectoscope is based on the following features of THz SPPs: 1) the high sensitivity of their characteristics (in particular the phase velocity and the propagation length) to optical characteristics of the waveguiding surface [5]; 2) the ability to overcome air gaps between their guide substrates with high efficiency [9]; 3) 100% reflection from a flat mirror placed across the track [6].

![Figure 4](image-url)

Figure 4. Schematic for detecting the inhomogeneity 10 on the surface 9 of a metal product using the Michelson surface plasmon interferometer of the THz range. The numbering of the interferometer elements is saved in accordance with Figure 1. The upper white arrow indicates the direction of the product movement in monitoring.

Before the start of measurements, a reference interferogram should be obtained when placing mirror 5 on substrate 3. After that, substrate 3 and controlled facet 9 of the product are brought into contact with their side faces and disposed in the same plane, while mirror 5 is fixed within the penetration depth of the SPPs field into the air (up to 3λ) above facet 9. Then the product is discretely shifted along the x-axis and, by scanning mirror 6, an interferogram is registered after each step of the product’s displacement.

If the controlled facet 9 does not contain inhomogeneities, then the interferograms are identical to the reference one (obtained when mirror 5 is disposed onto substrate 3) described by the expression (1). If, after a next step of moving the product, an inhomogeneity of width c is encountered on the path of the probing SPP-beam (see figure 4), this will cause the interferogram to shift by a value of:
\[ \delta x = \frac{\lambda_{\text{SPP}} \cdot \Delta \phi_c}{2\pi} = \frac{\lambda_{\text{SPP}} \cdot 2k_0 \cdot c \cdot (\kappa'_c - \kappa')}{2\pi} = \frac{\lambda_{\text{SPP}}}{\lambda} \cdot 2c \cdot (\kappa'_c - \kappa') = 2\kappa'c \cdot (\kappa'_c - \kappa'), \]  

(4)

here \( \lambda_{\text{SPP}} \) is the wavelength of the SPPs running onto substrate 3 and onto those parts of the controlled facet 9 which do not contain inhomogeneities; \( \Delta \phi_c = 2 \cdot k_0 \cdot c \cdot (\kappa'_c - \kappa') \) is the increment of the SPP phase which the SPPs gain when passing the section of facet 9 with inhomogeneity; \( \kappa'_c \) is the value of \( \kappa' \) on the section containing the inhomogeneity. Note that the period of the pattern \( \Lambda \) does not change after its shift, since the probing SPP beam recovers its value of \( \kappa' \) as soon as the beam passes the inhomogeneity.

Interaction of the SPP probe beam with an inhomogeneity leads not only to a shift of the interferogram, but also to a decrease in its contrast due to additional attenuation of the SPPs in the area with the inhomogeneity. An analytical expression describing a deformed interferogram has the form:

\[ I_{\text{int}}(x) = I_o \cdot R \cdot T \cdot \left\{ \exp\left[ -\alpha \cdot (2b - 2c + x) + \alpha_c \cdot 2c \right] + \exp\left[ -\alpha \cdot (2x + a) \right] + \exp\left[ -2\alpha \cdot (b - c + x + a) \right] + \exp\left( -2\alpha_c \cdot c \right) \cdot \cos(\Delta \phi^*) \right\}, \]  

(5)

here \( \Delta \phi^* = \Delta \phi + \Delta \phi_c = 2k_0 \cdot \kappa'_c \cdot \left[ x_0 - x \right] + 2 \cdot k_0 \cdot c \cdot (\kappa'_c - \kappa'); \alpha_c = 2k_0 \cdot \kappa''_c; \kappa''_c \) is the value of \( \kappa'' \) on the section containing the inhomogeneity; the other characters have the same meanings as in (1).

2.2. Numerical simulation of the interferogram shift in the interaction of the SPP probe beam with an inhomogeneity

Let the interferometer substrate and the controlled flat facet be made of gold with \( \omega_x = 215 \text{ cm}^{-1} \) and \( \omega_\rho = 72800 \text{ cm}^{-1} \), whose dielectric permittivity, as in Section 1.2, is calculated using the Drude model. We assume that the surface of the substrate contains an inhomogeneity in the form of a strip of zinc sulphide with its width \( c \) (the size along the track of the SPP probe beam) with thickness \( d_{\text{ZnS}} \) and the refractive index \( n_{\text{ZnS}} = 2.95 + i0.01 \) [8].

**Figure 5.** Calculated dependences of the displacement \( \delta x \) of the SPP-interferogram when a ZnS strip is detected on the Au surface under control: (a) the strip is 1 micron thick, but of different width \( c \); (b) the strip is 10 mm wide, but of different thickness \( d_{\text{ZnS}} \).
First, we shall model the dependence of the interferogram offset when ZnS strip of thickness $d_{ZnS}=1.0 \, \mu m$ is disposed across the SPP-track from the width $c$ of this “inhomogeneity”. For the radiation with $\lambda=130 \, \mu m$, the value of the real part of the refractive index of the SPPs at the “Au - Vacuum” interface is $\kappa'=1.000001$, while its value in the "Au - 1 \, \mu m ZnS-layer - Vacuum" is $\kappa''_c=1.000991$. Then, in accordance with formula (4), the dependence plot is a straight line, shown in figure 5a. It follows from the calculations that, with the "step" $\Delta c=1 \, \mu m$ of mirror 6, the THz surface plasmon defectoscope enables one to determine the ZnS layer width $c$ with an accuracy of 0.5 mm.

Next, we estimated the sensitivity of the interferogram to the thickness of the ZnS strip of width $c=10 \, mm$. The calculated plot of the dependence $\delta x(d_{ZnS})$ is presented in figure 5b. Its analysis shows that at $\Delta c=1 \, \mu m$, the THz surface plasmon defectoscope enables determining the thickness of 10 mm wide ZnS strip with an accuracy of 10 nm to 100 nm, depending on the $d_{ZnS}$ value.

3. Conclusion

Thus, the paper shows that the elaborated surface plasmon-polariton Michelson interferometer of the terahertz range can be effectively used not only for determining the thickness of the dielectric coating of a metal product, but also for detecting sub-wave thickness inhomogeneities on its surface. A displacement of the interferogram, occurring when the probing SPP beam meets on its way sites with different properties of the surface, may serve as an indicator of the presence of an inhomogeneity on the surface.

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