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METHODOLOGICAL NOTES

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Conversion of surface plasmon polaritons into photons: visual observation

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Abstract. **We present a simple experimental arrangement to observe the conversion of surface plasmon polaritons into photons at the edge of a metal plate.**

The term "surface plasmon polariton" (SPP) is used in reference to quasiparticles that emerge in the interaction of photons and electrons in a metal. These quasiparticles are coupled to the metal surface and propagate in the form of a surface electromagnetic wave along the interface between the metal and the vacuum or air (in the simplest case), with a momentum greater than the momentum of ordinary bulk waves [1]. The SPP amplitude decreases exponentially away from the surface, both with the depth into the metal and with the distance above the surface. Similar waves above the conducting terrestrial surface have been known as Zenneck waves since the beginning of the 20th century [2]. Strictly speaking, the term 'Zenneck waves' is used in refer to 'fast' electromagnetic waves that emerge at the interface between media one of which is conducting (sea water, wet terrestrial surface). When the contacting media have real permittivity parts of opposite sign, the 'slow' surface wave at their interface is referred to as a Fano wave. It is noteworthy that the experimental observation of Zenneck waves is still a topical problem (see, e.g., the recent discussion in *Physics–Uspekhi* [3, 4]), while Fano waves (SPPs) are being actively studied and used in many laboratories [5].

When SPPs travel along a wedge-shaped metal surface, on approaching the edge of the wedge they may either transit to its other side or detach from the wedge to transform into photons. The SPP–photon conversion of thermal SPPs, which formed a two-dimensional Bose gas with a Planckian spectrum, was observed in [6] at the rectangular edge of a copper plate. Figure 1 shows a photograph of this effect for a rectangular edge of a 15 mm wide and 5 cm long molybdenum plate 0.5 mm in thickness. The plate was heated to 85 °C; the observation was made with a ThermaCAM SC3000 (FLIR Systems) thermal infrared imaging unit in the 8–9 μm wavelength range. The side facet of the plate was oriented parallel to the thermal infrared imager. It can be seen that the brightness of radiation emanating from the regions adjacent to the horizontal plate edges exceeds the brightness of the central part of the side facet of the plate. This excess is so significant that the impression unconsciously forms that the temperatures of the plate regions located near the horizontal plate surfaces and of its central part are different, which is certainly not the case for the plate thickness indicated above.

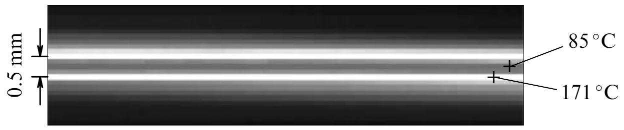

Figure 1. Image of a side facet of a heated molybdenum plate. According to infrared imager data, the temperature of the central part of the facet is 85 °C and the temperature of the regions adjacent to the plate edges is 171 °C.

This photograph also shows clearly that the Lambert law, which applies to blackbody radiation, is inapplicable to the thermal radiation of real bodies. We recall that according to this law, the brightness of the thermal radiation of a heated body is equal in all directions [7].

The theory of SPP conversion into real photons at the edge of a conducting wedge was formulated by Malyuzhinets [8]. The results, unfortunately, remained little known, as is evidenced, for instance, by Refs [9–11]. To an extent, this is because the results outlined in Ref. [8] are based on the unpublished doctoral thesis of the author defended at the Lebedev Physical Institute in 1950. This thesis gave a generalization of the classical Sommerfeld problem of the electromagnetic wave diffraction from a perfectly conducting wedge to the case of a wedge with finite conductivity. To make this generalization, Malyuzhinets developed a novel technique, which was recently described in monograph [12]. While the inclusion of a finite wedge conductivity for diffraction is merely a refinement of the theory, albeit an important one, the inclusion of a finite conductivity for SPPs is of fundamental significance because just the finite conductivity defines the width of the directivity pattern of conversion photons (see below). A more detailed description of Ref. [8], as well as certain modifications of the results arising from the inclusion of the difference between the acoustic impedance considered in Ref. [8] and the electromagnetic one emerging in the SPP theory, are given in [13, 14].

In the Malyuzhinets theory, the angular distribution $P(\alpha)$ of photons arising from SPP conversion is given by rather

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cumbersome formulas [13, 14]. But in the vicinity of its peak, this angular distribution for a rectangular wedge is Lorentzian, with the width defined by the imaginary part of the surface impedance ζ of the metal:

$$P(\alpha) = \frac{|\mathrm{Im}\,\zeta|}{\pi}\,\frac{1}{\alpha^2 + |\mathrm{Im}\,\zeta|^2}\,. \qquad (1)$$

The angle α is measured from a straight line that lies in the metal surface plane along which the SPPs propagate and is normal to the surface edge. The impedance in the SI system signifies the metal impedance relative to the impedance of the vacuum. The physical meaning of this symmetry of the angular distribution is quite clear: the photons are emitted primarily in the direction of the SPP propagation.

Malyuzhinets generalized the Sommerfeld problem using Leontovich's approximation, which assumes small values of the impedance. Strictly speaking, this approximation becomes inapplicable at the edge of the wedge, where the surface curvature formally tends to zero [2]. Unfortunately, attempts to obtain the exact solution of this problem do not meet with success, and good agreement of the experimental data reported in [6] with formula (1) may be taken to signify that the violation of Leontovich's approximation at the edge of the wedge is not critically significant to the SPP–photon conversion effect under consideration.

It follows from formula (1) that the magnitude of the imaginary part of the surface impedance of a metal can be measured by measuring the width of the angular distribution of the photons arising from SPP–photon conversion at a rectangular metal boundary. The accuracy of measurements in the infrared domain may then far exceed the accuracy of traditional techniques [15], which was demonstrated in [16]. We recall that the imaginary part of the impedance of good conductors is much greater than its real part in the optical and infrared ranges. We also emphasize that the impedance determines the optical properties of a metal under the conditions of the anomalous skin effect, when the permittivity of the metal makes no sense (see, e.g., [17] and the references therein). In the normal skin effect, $\zeta = (\mu/\varepsilon)^{1/2}$, where μ and ε are the permeability and permittivity of the metal.

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