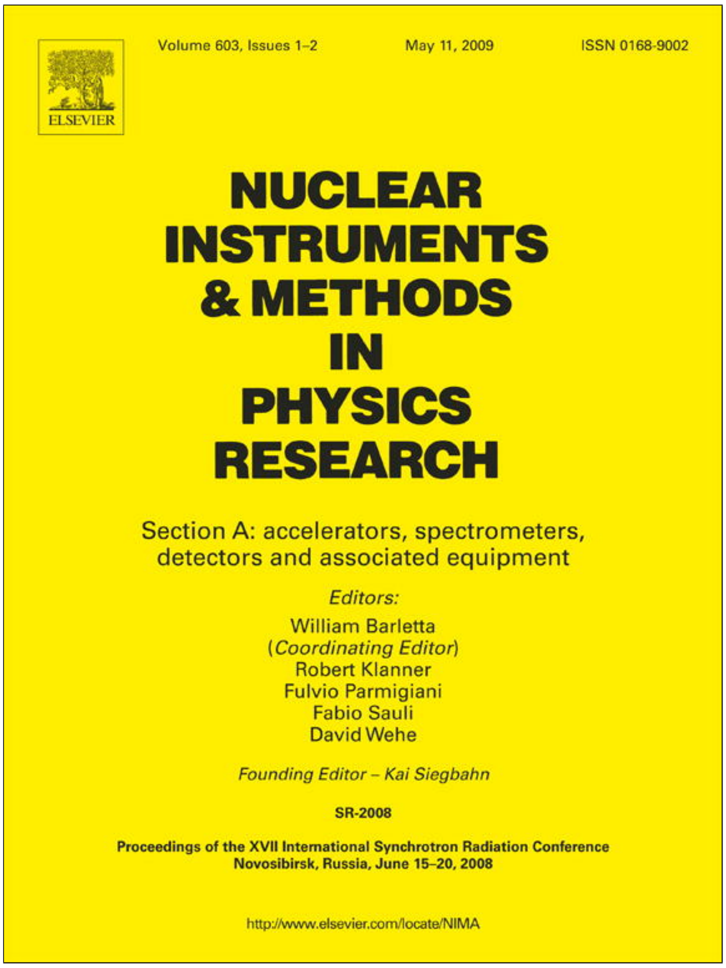

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Geodesic elements to control terahertz surface plasmons

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ABSTRACT

Geodesic elements (prisms, lenses, and beam splitters) are suggested to control (focus, deflect, and split) beams of terahertz (THz) surface plasmons (SPs). A geodesic deflector made in the form of conical trench crossing a SP beam can be effectively used not only for deflection of the beam but also for separation of surface and bulk electromagnetic waves. Formulae for calculating the angle of SP beam deflection with a geodesic prism as well as the angle of divergence of SP beams at the output of the geodesic splitter have been obtained. Schemes of THz SP absorption sensor and interferometer based on geodesic elements are discussed as well.

1. Introduction

Intensive development of the terahertz (THz) spectral range (frequencies from 0.1 to 10 THz) started in the early 90s, when tunable free-electron lasers and pulsing femtosecond lasers were designed and built [1]. The most important applications of THz radiation include molecular spectroscopy of thin films and communication by surface electromagnetic waves, particularly by surface plasmons (SPs) propagating along a "metal–dielectric" interface [2]. The main advantage of THz SPs use in communication devices is their high-phase velocity, which is smaller only by hundredths of a percent than the speed of light in air [3]. This makes it possible to reduce the snapping time of the devices.

At development of systems employing SPs as an information carrier, such elements such as deflectors, beam splitters, and lenses will be definitely in great demand to control THz SPs. First investigations on THz SP lenses and deflectors have already been reported [4,5].

In this paper, we consider the problem of controlling THz SP beams by means of geodesic elements formed in the surface of a specimen. It is stated that a geodesic prism fabricated in the form of a trench of conical shape can be used not only for deflection of THz SP beams but also for separation of overlapped bulk and surface waves. The overlapping occurs at transformation of bulk radiation into SPs due to diffraction (on the edge of a screen placed close to the specimen surface or on a grating formed on it) [6,7].

We realized the urgency of THz SPs control problem while performing experiments on SPs excitation and detection using free-electron laser radiation [8]. First, the efficiency of SPs excitation on a bare metal surface by the method of diffraction was very small (less than 1%) [9]. That is why the SPs field intensity in the experiments performed was comparable with the background noise, which made us think about some focusing of the SP beam. Second, there was large parasitic illumination of the detector by diffracted bulk waves produced on the screen's edge. To do away with the problem it was suggested to place an excitation element on the adjacent side of the specimen [6] or to fabricate a deep cylindrical trench across the SP trace right after the input element and place a nontransparent screen along the trench axis on the level of the specimen surface in order to absorb the bulk waves [10]. But with these techniques, we did not succeed in getting rid of the illumination noise without unacceptable decrease in the SPs intensity.

Similar to planar optical waveguide modes, SPs are surface electromagnetic waves. That is why we anticipated that one could succeed in SP beam control with planar elements used in integrated optics [11]. However, calculations indicate that at THz frequencies such planar optical elements as mode-index, Luneburg or diffractive (Fresnel) lenses are not effective or fail at all. The point is that THz SPs field in air is specific not only in reaching maximum on the guiding surface but also in its spatial distribution, which is very similar to plane wave propagating along the surface [12]. That is why planar gratings used without any thin-film coverage influence THz SPs characteristics very slightly [13],

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while a localized inhomogeneity coated on the specimen surface at the formation of a Luneburg lens may strongly deform the SPs field and give rise to an undesirable transformation of SPs into bulk waves.

2. Design of geodesic elements to control THz SPs

Geodesic elements do not distort SPs field distribution but change the direction of SPs propagation. This is precisely the reason why we favored geodesic structures in an effort to control weakly attenuated beams of THz SPs.

Both theory and practice of geodesic lenses are well developed in integrated optics [14,15] and are true for THz SPs, which have extinction comparable with that of optical dielectric and metal–dielectric waveguide modes. In particular, the focal distance F of a spherical geodesic lens is given by [15]

$$F = \frac{R}{2(1-\cos\theta)} \tag{1}$$

where R is the radius of the depressed surface at the intersection of the specimen plane and θ is the half-angle of the chord.

We have not found any publications about geodesic prisms in integrated optics and had to develop the theory of these prisms as applied to THz SPs. That is why we set ourselves the task of determining the terms when a geodesic prism deflects a collimated THz SPs beam without distorting its wave front and deriving a formula for calculating the angle of SPs deflection from its initial direction of propagation. Below, we present a detailed derivation of the formula.

Suppose that SPs characterized by a complex index of refraction $\kappa=\kappa'+i\kappa''$ (i is the imaginary unit) propagate in the form of a beam of parallel rays of a width d along a plane surface. Let an inhomogeneity in the form of a trench be created in the surface normal to the initial wave vector of the SPs (Fig. 1). We shall prove that if the trench has the form of a right cone with its axis lying in the specimen surface, such a trench ensures that SPs optical path depends linearly on the coordinate x, i.e. such a trench is a geodesic prism capable of turning the SPs wave front through an angle γ.

Let us estimate ΔS_o, the difference in the geometrical paths of the extreme rays of the SPs beam incident on the trench, introducing the following notations: R_o is the radius of the "cone" base, R is the current radius of the trench surface, which depends on the coordinate x, H is the "height" of the "cone" (equal to the beam width d). To determine ΔS_o we will single out on the specimen surface, a box enveloping the trench having dimensions $2R_o \times H$.

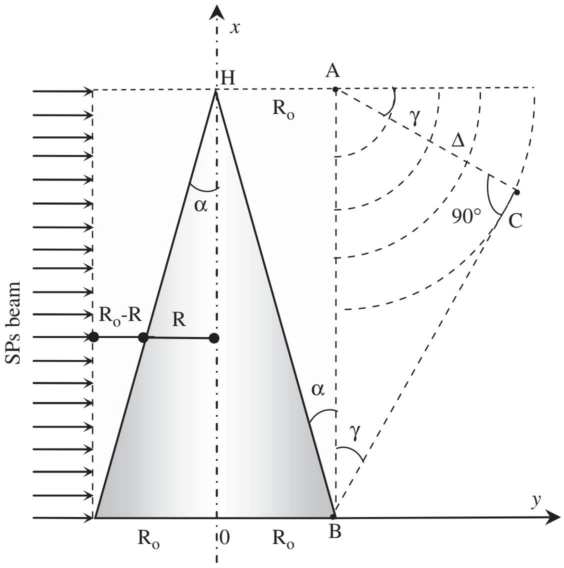

Fig. 1. SPs beam with plane wave front overcoming the inhomogeneity with dimensions $2R_o \times H$ containing a conical trench.

The geometrical path S_o of an arbitrary SP ray inside the inhomogeneity depends upon the coordinate x as follows: $S_o(x)=2(R_o-R)+\pi R=R_o[(x/H)(2-\pi)+\pi]$, where it is taken into account that $R=(R_o/H)(H-x)$. Hence, the value of S_o depends linearly on x.

Furthermore, the geometrical path difference ΔS_o for the extreme rays of the beam (characterized by the coordinates $x=0$ and H) is given by $\Delta S_o=S_o(0)-S_o(H)=R_o(\pi-2)$, while the optical path difference of these rays is given by $\Delta S=\Delta S_o\kappa'=R_o(\pi-2)\kappa'$. Therewith, the ray with coordinate $x=H$ will cover the box faster than the ray with the coordinate $x=0$. The time interval is $\Delta t=\Delta S/\vartheta=[R_o(\pi-2)\kappa']/(C/\kappa')$, where ϑ is the phase velocity of SPs, C is the speed of light in vacuum. That is why the point A becomes a source of secondary waves with circular wave fronts by Δt earlier as compared with the point B. During the time interval Δt, the secondary waves will cover the distance $AC=\vartheta\cdot\Delta t=\Delta S=R_o(\pi-2)\kappa'$.

Finally, from the rectangular triangle ABC one can find that $\sin(\gamma)=AC/H=[R_o(\pi-2)\kappa']/H=\tan(\alpha)(\pi-2)\kappa'$. Thus, the final formula for calculating γ, the angle of SP beam deflection by a conical trench, looks as follows:

$$\gamma = \arcsin[\tan(\alpha)(\pi-2)\kappa'] \tag{2}$$

Note that the angle γ depends upon $\tan(\alpha)$, i.e. upon the ratio of the trench radius R_o to the beam width d. Therefore, the method for deflecting a SPs beam with a conical trench can be used only under the condition that the SPs propagation length exceeds well the trench radius R_o. Otherwise, the SPs will dissipate on their way across the trench. This condition is met for SPs in the THz range as at these frequencies the SPs propagation length reaches dozens of centimeters and even more [3,12].

The dependence of $S_o(x)$ is not linear if the axis of the cone does not lie in the specimen surface, which results in divergence of the SP rays that have covered the trench. This leads to a distortion in the wave front, which is unacceptable for beam deflectors. But the requirement on the cone top location in the beam span is not a prerequisite; formula (2) is also valid for a case when the cone top is out of (or inside) the beam margins.

And one more remark in conclusion of this paragraph: to reduce radiation losses one has to smooth the trench edges with a radius of rounding r satisfying the condition $r \gg \lambda$, similar to formation of geodesic lenses [14,15].

By the example of SP geodesic prism operation, let us calculate the value of the angle α between the moving line of the conical trench and its axis to deflect a collimated SPs beam excited with monochromatic radiation ($\lambda=110\,\mu$m) on a plane aluminum surface bordering air to the angle γ equal to 30°. In this case, the real part of the SP refractive index is $\kappa'=1.0005$ and the SPs propagation length calculated using the Drude model for aluminum dielectric permittivity equals 685 cm, which meets the mentioned condition for the relation between the SPs propagation length and the cone "basement" radius R_o with a safety margin. Substituting values for κ' and γ in Eq. (2), we get $\alpha \approx 24^\circ 40'$.

Another available geodesic element for THz SPs optics is a beam splitter, which may be used in SP interferometers, sensors, spectrometers, communication, and processing devices. A single geodesic prism described above and partially spanning the incident SP beam cannot split the beam in a proper way as the beam part passed by the prism continue to coincide with the bulk waves produced on the SPs input element, and that gives rise to parasitic illumination of the photo detector.

A system of two conjugated geodesic prisms whose axes coincide and lie in the specimen surface can play the role of SPs beam splitter more effectively (Fig. 2). The condition of coincidence of the prisms tops is not binding; location of the tops in the trench axis is quite sufficient. It is evident that the splitting angle γ between the new diverging SP beams equals the sum of the deflection angles γ_1 and γ_2 introduced by each of the prisms:

$$\gamma = \gamma_1 + \gamma_2 = \arcsin[\tan(\alpha_1)(\pi - 2)\kappa'] + \arcsin[\tan(\alpha_2)(\pi - 2)\kappa'], \tag{3}$$

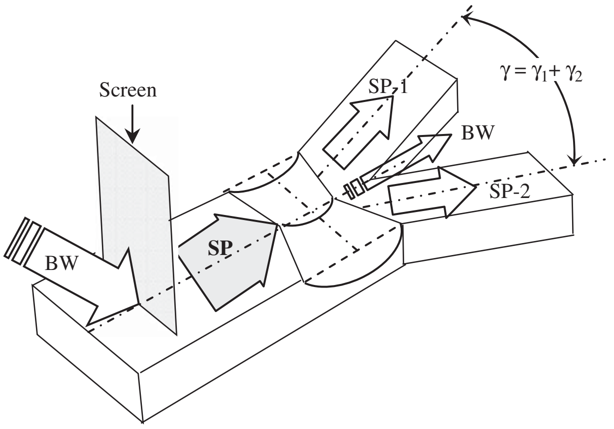

Fig. 2. Geodesic SPs beam splitter: BW—bulk wave; SP—initial SP beam; SP-1 and SP-2—new SP beams.

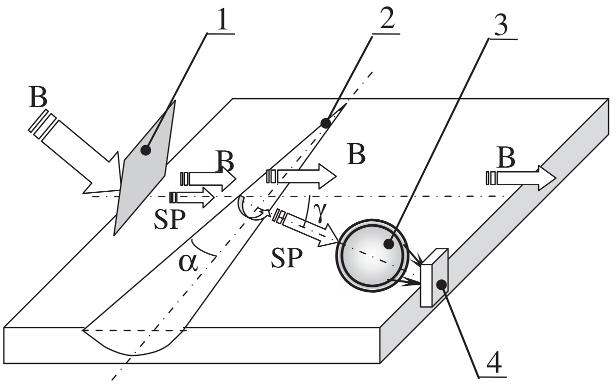

Fig. 3. Scheme of the THz SPs absorption sensor: (1) aperture; (2) geodesic prism; (3) geodesic lens; and (4) detector.

where α_1 and α_2 are the angles between the moving lines of the prisms and their common axis, respectively.

Such SP beam splitters can be utilized in SP interferometers, sensors, and communication devices.

3. THz SPs devices employing geodesic elements

3.1. Absorption sensor

Infrared SP absorption spectrometers were developed long ago and are used both for obtaining absorption spectra of thin films on solid surfaces and for refractometry of metals [16,17]. These devices measure the SP propagation length. Until recently, the SPs propagation length was usually determined using the two-prism method, implying measurements of the SPs field intensity at least at two points spaced in the surface wave track [18].

Here, we suggest a scheme of infrared SPs absorption sensor able to detect either thin films on a conducting substrate or external actions changing the SPs propagation length (Fig. 3). Main advantages of this sensor are as follows: first, we get rid of the bulk radiation background noise by directing the original SPs beam onto a geodesic prism separating the bulk and surface waves; second, using a geodesic lens, we concentrate the energy of the deflected SPs beam on the detector, and thus increase the luminosity of the device. Moreover, there are no moving parts in the sensor.

3.2. THz SP interferometer

As THz SPs have a small attenuation factor, Mach–Zehnder interferometer devices utilizing SPs can be developed. Here, we present a scheme of THz SP interferometer able to determine both parts of the SPs complex refractive index $\kappa = \kappa' + i\kappa''$. The interferometer implements the concept of static asymmetric interferometry [19]. The key point of the interferometer operation is that the analyzed interference pattern (registered in the specimen surface plane) is formed by surface waves instead of bulk waves. The interferogram contains information about both parts of κ: the period of the pattern is inversely proportional to κ', while intensity variations in the maxima of the pattern are linked with κ''.

The scheme of the THz SPs interferometer is given in Fig. 4. The device functions are as follows: continuous laser radiation 1 falls on the diffractional element 2 and excites SPs with certain efficiency. As stated above, the process of bulk radiation transformation in SPs is accompanied by production of diffracted bulk waves, which propagate along the specimen surface 3, overlapping with the SPs. On reaching the beam

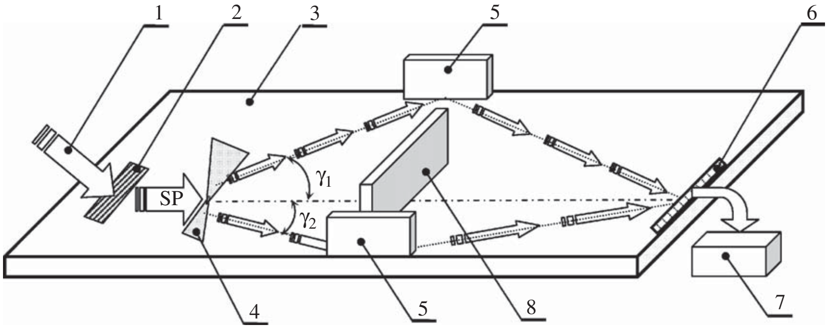

Fig. 4. THz SPs interferometer intended to measure the SPs refractive index and its changes: (1) bulk wave; (2) diffraction element; (3) specimen; (4) geodesic beam splitter; (5) plane vertical mirrors; (6) photo detector array; (7) computer; and (8) absorber of the bulk waves produced on the element 2.

splitter 4 (two conjugated geodesic prisms), the superposed waves are separated: two new beams of SPs diverge at the angle γ specified by formula (3), while the bulk waves go on propagating in the plane of incidence. Further, the new beams of SPs are reflected by the mirrors 5, placed normal to the specimen surface at different distances from the plane of incidence, and fall at the photo-detector array 6. Here, they form an interference pattern which is registered by the array and analyzed by the computer 7. Meanwhile, the diffracted bulk radiation is eliminated by the absorber 8.

Note that the suggested SPs interferometer may be used effectively for sensing various processes (such as adsorption, chemical reactions, condensation, mechanical displacement or approach of an object to the surface, etc.) going on the plane surface of conducting objects or in its vicinity.

4. Conclusion

In conclusion, we should mention that the development of terahertz plasmonics is in the course of mastering the terahertz spectral range as a whole [2]. At present, practically all elemental foundation necessary for THz plasmonics advance has been developed, namely sources of THz radiation (synchrotrons, tunable free-electron lasers, femtosecond pulsing lasers, backward-wave tubes, quantum cascade lasers, etc), sensitive receivers (photoconducting dipole antennas, bolometers, piroelectric detectors, and photo resistors), and visualizers.

That is why it is urgent to develop optical elements able to control THz SPs beams. Geodesic devices (prisms, lenses, and beam splitters) are among them. We hope that geodesic prisms and beam splitters will be widely used in infrared surface plasmonics in the nearest future.

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