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Massive surface-plasmon polaritons

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Abstract: It is well-known that a quantum of light (photon) has a zero mass in vacuum. Entering into a medium the photon creates a quasiparticle (polariton, plasmon, surface-phonon, surface-plasmon polariton, etc.) whose rest mass is generally not zero. In this letter, devoted to the memory of Mark Stockman, we evaluate the rest mass of light-induced surface-plasmon polaritons (SPPs) and discuss an idea that collisions of two massive SPP quasiparticles can result in changes of their frequencies according to the energy and momentum conservation laws.

Keywords: localized plasmons; quantum plasmonics; surface-plasmon polaritons.

This letter is devoted to the memory of a great scientist and friend Mark I. Stockman who left a brilliant track record in the fields of nanophotonics and plasmonics [1–6]. At present, investigations of the discrete nature of light and single photon experiments are opening a new era of quantum photonics and quantum plasmonics [7]. Entering into a medium the photon creates a quasiparticle (polariton, plasmon, surface-phonon, or surface-plasmon polariton). Quasiparticles are not quite particles but they are real and behave in the way similar to the behavior of particles. Classification of the existing photonic quasiparticles can be found in a recent review [8]. When a particle (or quasiparticle) is moving with the velocity v smaller than the velocity of light in vacuum $v < c$, it has a non-zero rest mass m, according to the well-known special relativity equation $E\sqrt{1 - v^2/c^2} = mc^2$, where E is the particle (or quasiparticle) energy. In this letter, we consider surface plasmon polaritons (SPPs) which are TM electromagnetic waves coupled to electron oscillations at a metal-dielectric interface from the quasiparticle point of view. In memory of Mark I. Stockman and his ability to look at problems from unexpected side, we consider SPPs as massive quasiparticles and provide estimates of their mass. We discuss conditions when the SPP rest mass can become comparable with the rest mass of electron and a possibility of frequency conversion of SPPs during their collisions.

To simplify theoretical analysis, we neglect absorption both in dielectric and metal. This approximation can be used if the SPP propagation length is much larger than its wavelength. This allows to characterize metal by a real frequency-dependent dielectric function $\epsilon_m(\omega)$ [9, 10]. The dispersion relation for single interface SPPs is well-known and is determined by $k_{\mathrm{SPP}} = n\omega/c$ with

$$n = \sqrt{\frac{\epsilon_{\mathrm{d}}\epsilon_{\mathrm{m}}(\omega)}{\epsilon_{\mathrm{d}} + \epsilon_{\mathrm{m}}(\omega)}} \qquad (1)$$

where k_{SPP} is the SPP wavenumber, ω is its frequency, n is the effective refractive index, ϵ_{d} and ϵ_{m} are the dielectric and metallic permittivities. We keep here explicitly only the frequency dependence of the metallic permittivity approximated by free electron model [11]. SPPs exist at the frequencies $\omega < \omega_{\mathrm{SP}} = \omega_{\mathrm{p}}/\sqrt{\epsilon_{\mathrm{d}} + 1}$, where ω_{p} is the plasma frequency. The phase velocity of SPPs is determined by c/n, and the group velocity $v_{\mathrm{g}} = c/n_{\mathrm{g}}$ is determined by the group refractive index n_{g}

$$n_{\mathrm{g}} = n + \omega\frac{\mathrm{d}n}{\mathrm{d}\omega} = n + \frac{\omega}{2n}\frac{\epsilon_{\mathrm{d}}^2\epsilon'_{\mathrm{m}}(\omega)}{[\epsilon_{\mathrm{d}} + \epsilon_{\mathrm{m}}(\omega)]^2}, \qquad (2)$$

where $\epsilon'_{\mathrm{m}}(\omega) = \mathrm{d}\epsilon_{\mathrm{m}}(\omega)/\mathrm{d}\omega$.

In case of $n \gg 1$ and $n_{\mathrm{g}} \gg 1$, both phase and group velocities are much smaller than the speed of light, and we can use classical nonrelativistic mechanics in further discussions (a general case of relativistic velocities can be easily derived following recent paper devoted to photon properties in a dielectric medium [12]). The SPP quasiparticle can be considered as a field oscillator. According to the virial theorem for an oscillator [13], its average kinetic and potential energies are equal giving the following relation for the total energy of the SPP quasiparticle

$$\hbar\omega = mv^2. \qquad (3)$$

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At very low frequencies, when $\omega \ll \omega_{\mathrm{SP}}$, the frequency dependence of the refractive index can be neglected so that $n \simeq \sqrt{\epsilon_{\mathrm{d}}}$. In this case, the SPP quasiparticle is similar to the photon in medium and propagates with the velocity $v = c/n$. Introducing this velocity in Eq. (3), we get the mass of the SPP quasiparticle $m = n^2\hbar\omega/c^2$ and its momentum $p = n\hbar\omega/c$. At higher frequencies, approaching ω_{SP}, the dispersion is important, and the SPP quasiparticle propagates with the group velocity $v = v_{\mathrm{g}} = c/n_{\mathrm{g}}$. Introducing this velocity in Eq. (3), we get another expression for the mass of the SPP quasiparticle $m = n_{\mathrm{g}}^2\hbar\omega/c^2$ and its momentum $p = n_{\mathrm{g}}\hbar\omega/c$. The mass of SPP quasiparticle with $\hbar\omega = 2\,\mathrm{eV}$ (orange color) will be equal to the rest mass of electron $m_{\mathrm{e}} \simeq 0.511$ MeV for $n_{\mathrm{g}} \simeq 505$. At high values of the refractive index, the SPP quasiparticle momentum is very high and is equal to the momentum of X-ray photons at the wavelength $\lambda_x = \lambda/n$, where $\lambda = 2\pi c/\omega$.

Using the language of quasiparticles and classical mechanics, collision between two SPPs with different energies $\hbar\omega_1$ and $\hbar\omega_2$, according to energy and momentum conservation laws, can result in energy exchange between them producing SPPs at $\hbar\omega_1'$ and $\hbar\omega_2'$ with different frequencies, which could be experimentally observed. This process is similar to nonlinear four wave mixing. In this case, SPPs behave similar to collective "matter" waves, which are highly nonlinear, and the result of their collision is determined by the Coulomb interaction of the involved charges. In this picture, nonlinear frequency conversion of SPPs can happen at low intensities corresponding to quantum plasmonics. Recently, lightwave-driven quasiparticle collisions on a subcycle timescale have been experimentally studied in [14].

In conclusion, we considered SPPs as massive quasiparticles and derived expressions for their mass using dispersion relation and the virial theorem for an oscillator. The suggested approach allowed to find conditions when the SPP rest mass can become comparable with the rest mass of electron. Note that the experimental generation and observation of massive SPP quasiparticles could be challenging. Investigations of collisions between the SPP quasiparticles can provide interesting information about their internal structure and properties. Such collisions can result in frequency changes of SPPs similar to four wave mixing, which could be important for quantum plasmonics.

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Conflict of interest statement: The authors declare no conflicts of interest regarding this article.

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