Enhanced Dynamical Casimir Effect for Surface Plasmon Polaritons and Guided Dielectric Waves

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Abstract: Dynamical Casimir effect – emission of surface waves due to oscillations of optical length of resonator under laser excitation is considered. If amplitude of oscillations coincides with wavelength of emission then its strong enhancement takes place.

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1. Introduction

Electromagnetic waves confined in a planar interface or in a dielectric hetero-structure, may have a strongly enhanced field. These waves are of great interest for various applications, as they allow one to strongly amplify the interaction of light with matter. This is especially important for weak optical processes, which otherwise are difficult to observe and to employ. Here we are considering the possibility of using these waves for the enhancement of a spontaneous emission of pairs of electromagnetic excitations quanta in a resonator when its optical length changes in time under laser excitation. This emission is known as the dynamical Casimir effect (DCE) [1,2], and it arises due to the time-dependent perturbation of the zero-point state. The consideration presented here holds for surface plasmon polaritons (SPPs) in metal-dielectric interfaces, for guided 2D-waves propagating along a thin dielectric slab with high refractive index surrounded by dielectrics with smaller refractive indices (guided dielectric waves (GDWs)) and for the D’yakonov waves existing in the interface of dielectrics of different symmetry.

2. The yield of emission due to DCE

The scheme of experiment under consideration allowing one to generate SPP- or GDW-quanta is presented in Fig. 1. Here a metal-dielectric interface or a dielectric hetero-structure is placed to the resonator and irradiated by a monochromatic laser wave with the frequency $\omega_b$ and wave front parallel to the interface ((x, y) plane of the laboratory reference frame). The length (in x direction) and the width of the interface respectively are $l_0$ and $l_f$; the optical length of a SPP is $L = n_0 l_0$. The generation of pairs of quanta takes place due to modulation in time of this length by the laser light. The generated quanta have the wave vectors $\vec{k} = (k_x, k_y)$ and $\vec{k}' = (k'_x, -k'_y)$. In order to get emission outside the resonator, the prism with high refractive index is added. Analogous set-up can be used for generation of pairs of quanta of D’yakonov waves.

The time dependence of the optical length of the resonator for SPPs or GDWs can be presented in the form $L = L + (a_0/2) \cos(\alpha_l \tau)$. The rate of emission of quanta caused by these oscillations is determined by the dimensionless parameter $v = \pi a_0/2\lambda_0$ [1, 2], where $a_0 \sim \eta^4 |\chi^{(2)}|^2 \sqrt{I_0 Z_0}$ is the amplitude of oscillations of the optical length, $\chi^{(2)}$ is the second-order nonlinear susceptibility, $\eta$ is the enhancement of the field, $\lambda_0 = 2\pi c/\omega_b$, $a_0$, and $I_0$ are the laser frequency and intensity, $Z_0 = 376.7$ ohm. In Ref. [3] it was shown that for $v \ll 1$ the yield of emission due to DCE equals

$$\zeta \sim 10^{-2} \eta^4 \hbar \omega_b^2 |\chi^{(2)}|^2 Z_0 / 2\lambda_0^3$$

( $l_0$ is the length of resonator). If $I_0 < 10^6$ W/m$^2$ and $\eta = 20$ (typical value) then $v \sim 10^{-3}$ and $\zeta \sim 10^{-7}$. But for long-range SPPs one can get $\eta \sim 10^2$ and $v \gtrsim 1$ already for $I_0 \lesssim 10^3$ W/m$^2$. In this case the theory [3] is not applicable.

3. Resonant enhancement of DCE

Here we present a theory of emission due DCE for SPPs, GDWs and/or which works also for $v \gtrsim 1$. We have found that the spectral rate of emission in direction $\theta = \arcsin(\Omega)$ is described by the equation
\[ I(\Omega, \vartheta) = v^2 I_0 \Omega^2 \cos \vartheta \sqrt{(1 - \Omega)^2 - \Omega^2 \sin^2 \vartheta} \left| 1 - v^2 G_\alpha(\Omega) G'_\alpha(1 - \Omega) \right|^2 \]

where \( \Omega = \omega \omega_0 \).

\[ G(\Omega) = \cos \vartheta \left[ 2 - 2\Omega \sin \vartheta + \Omega \ln \left( (1 - \Omega)(1 + \sin \vartheta)/(1 + \Omega)(1 - \sin \vartheta) \right) + i\pi \right]/2\pi \]

If \( v \ll 1 \) then the spectrum of emission is continuous. However if \( v \geq 2.94 \) then the emission under consideration became monochromatic (with \( \omega = \omega_0/2 \) ) and is resonantly enhanced (see Fig. 2). The corresponding value of \( v \) equals to \( v_r = 1/[G'_\alpha(1/2)] \). The dependence of the total rate of emission is given on Fig. 3.

From the consideration presented here it follows that the waves confined at a plain surface (SPPs, DGWs, DWs) allow one to strongly enhance spontaneous emission due to DCE. There exists an optimal intensity of excitation, corresponding to \( v_0 \approx 3 \) when this effect is strongly enhanced. The latter value of \( v \) is close to \( \pi \), which means that the enhancement takes place if \( a_0 \approx \lambda_0 \), i.e. if the full amplitude of oscillations of the optical length coincides with the wavelength of excitation (and with the half of the wavelength of emission). This phenomenon can be considered as a kind of parametric resonance describing a sharply enlarged response, here the enhanced spontaneous two-photon emission of the system at the specific value of the external parameter, here the intensity of laser excitation \( I_0 = I_c = 0.22 \lambda_0^2/|l^0| \eta^4 Z_0^2 \chi^{(2)} |Z_0^2| \). For long-range SPPs one gets \( I_c \sim 10^4 \text{ W/m}^2 \) which is rather moderate intensity of laser excitation.

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**4. References**

