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Spontaneous Parametric Down-Conversion and Dynamical Casimir Effect for Surface Plasmon Polaritons and Guided Waves

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Abstract. The features of biphotons states generated via spontaneous four-wave mixing in nanofibers with a variable cross-section are studied. The spectral amplitude of the biphoton field is calculated and the effects of interference and phase modulation of the biphoton field in such structures is discussed.

Keywords: spontaneous parametric down-conversion, dynamical Casimir effect, surface plasmon polaritons, guided waves.

Spontaneous parametric down-conversion (SPDC) and spontaneous emission of pairs of photons due to the dynamical Casimir effect (DCE) (see Ref. [1]) in the metal-dielectric interface are considered.

Dielectric is supposed to have a non-zero second-order nonlinear susceptibility $\chi^{(2)}$. Surface plasmon polaritons (SPPs) in the metal-dielectric interface lead to strong enhancement of the electric field of the electromagnetic modes. This allows to strongly intensify weak multiphoton processes. E.g. SPPs allow one to achieve a rather high yield of the SPDC if the excitation angle φ_0 corresponding to the Kretschmann configuration for the generated SPPs quanta is used (see the experimental scheme in Fig. 1). In this case the excitation creates the polarization wave in the interface, which propagates along the interface with the phase velocity $\omega_0 n_0 \cos\varphi_0 = c_0 / n_{sp}$ being equal to the phase velocity of SPPs with the frequency $\omega_1 = 0.5\omega_0$ (corresponding wave vector is $\vec{k}_0 n_0 \cos\varphi_0$). Therefore the running wave of polarization with the frequency ω_0 can generate the pairs of SPPs quanta with the same sum frequency and fulfill the phase-matching condition. The generated plasmons can transfer to photons in the Kretschmann prism with the propagation angle $\pi - \varphi_0$ (see Fig. 1).

The yield of SPDC in this case equals

$$\kappa = 10^{-2}\hbar\omega_p^2 Z_0 l_0^2 \lambda^{-4}\left(\eta_p(\omega_0)\eta_s(\omega_s)\eta_i(\omega_i)\right)^2 \left|\chi_{\text{eff}}^{(2)}\right|^2, \quad (1)$$

where Z_0 is the impedance of free space, l_0 is the coherence length, λ is the wavelength of the generated quanta, $\eta_p(\omega_0)$, $\eta_s(\omega_s)$ and $\eta_i(\omega_i)$ are the enhancement (renormalization) factors of the electric field of the pump, signal and idler waves. In usual crystals without inverse symmetry the

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estimated yield of SPDC is in the order of $\kappa \sim 10^{-12}$. However for SPPs one can get $\kappa \sim 10^{-7}$. Even larger yield one can get for long-range SPPs.

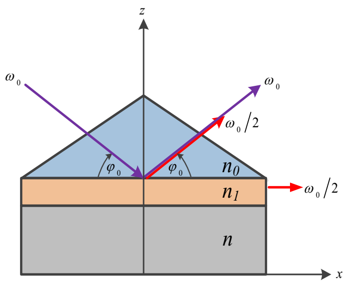

Figure 1. SPDC in the metal-dielectric interface. φ_0 corresponds to the Kretschmann angle for the frequency $\omega_1 = \omega_0/2$ of generated SPPs.

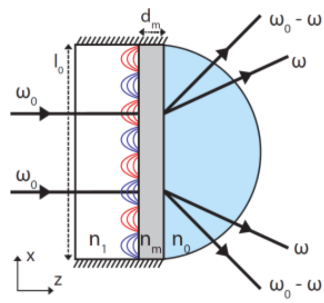

Figure 2. Dynamical Casimir effect for surface plasmon-polaritons. The prism transforms the generated quanta of SPPs to photons.

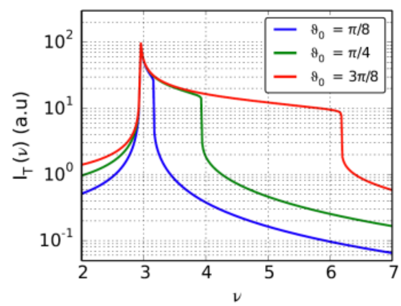

Figure 3. Total intensity of DCE-induced emission as a function of $\nu \propto \left|\chi^{(2)}\right| I_L^{1/2}$, $\vartheta_0 = \arctan(l_1/l_0)$, I_L laser intensity, l_0 and l_1 length and width of the interface.

Especially strong enhancement by means of SPPs one can achieve for dynamical Casimir effect (DCE) – the emission of pairs of photons due to oscillations in time of the of optical length of the resonator. The scheme of generation of photon pairs due to the DCE in the metal-dielectric interface is given in Fig. 2. In this scheme the oscillations of the optical length of the SPP modes in the resonator are induced by laser light. The yield of the DCE-induced emission in case of small amplitude of oscillations of the optical length a_0 as compared to the wavelength of excitation λ_0 equals [1]

$$\zeta \cong 10^{-2}\hbar\omega_0^2 l_0 \left(\eta_p(\omega_0)\eta_s(\omega_s)\eta_i(\omega_i)\right)^2 \left|\chi^{(2)}\right|^2 Z_0/2\lambda_0^3. \tag{2}$$

It is a few orders of magnitude less than the yield of SPDC for similar conditions. However if the amplitude of the oscillations of the optical length became comparable with the wavelength of generated quanta then DCE-induced emission may be strongly enhanced. In this case the spectral rate of the emission is described by the equation

$$I(\Omega,\vartheta) = \frac{\nu^2 l_1 \Omega^2 \cos\vartheta \sqrt{(1-\Omega)^2 - \Omega^2 \sin^2\vartheta}}{2\pi\lambda_0 \left|1-\nu^2 G_\vartheta(\Omega) G_\vartheta^*(1-\Omega)\right|^2}, \tag{3}$$

where $\nu = \pi a_0/2\lambda_0$, $\Omega = \omega/\omega_0$, ϑ is the angle of emission and

$$G_\vartheta(\Omega) = \cos\vartheta\left[2 - 2\Omega\sin\vartheta + \Omega\ln\left((1-\Omega)(1+\sin\vartheta)/(1+\Omega)(1-\sin\vartheta)\right) + i\pi\Omega\right]/2\pi. \tag{4}$$

The dependences of the total rate of emission on ν and emission angle ϑ for different widths l_1 of the interface are given in Fig. 3. From this figure one can see that SPPs indeed allow one to strongly enhance DCE-induced emission. The enhancement takes place for $\nu_r = 1/\left|G_\vartheta(1/2)\right| \geq 2.93$. The enhanced emission is well directed and is monochromatic with the frequency $\omega = \omega_0/2$.

Note that there exists an optimal intensity of excitation of DCE-induced emission, corresponding to $\nu \approx 3$. The latter value of ν is close to π, 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 wavelength of emission). This phenomenon can be considered as a kind of parametric resonance describing a sharply enlarged response of the system (here the spontaneous two-photon emission) at the specific value of the external parameter (here the intensity of laser excitation $I_0 = I_r = 0.22\lambda_0^2 / l_0^2\, \eta^4 Z_0 \left|\chi^{(2)}\right|^2$). For long-range SPPs one gets $I_r \sim 10^4$ W/m^2, which is rather moderate intensity of laser excitation.

The consideration presented here holds also for guided 2D-waves propagating along a thin dielectric slab with high refractive index surrounded by dielectrics with smaller refractive indices and for the Dyakonov waves existing at the interface of dielectrics of different symmetry.

In the present work we develop the theory of spontaneous four-wave mixing (SFWM) in irregular nanofibers. We calculate the effective refractive index and mode functions for nanofibers that are made of various promising materials. The optimal size of a nanofiber for implementing phase matching condition allowing generation of correlated photons at wavelengths 810 nm and 1550 nm is determined. The spectrum of SFWM in irregular nanofibers is calculated and some interesting phenomena such as interference and phase modulation of the biphoton field, the description of which requires considering the effective refractive index as a function of the longitudinal coordinate, are discussed.

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Reference

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