Interference of zero-point fluctuations of the electromagnetic vacuum and photon correlation in parametric light scattering

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Spontaneous three-photon parametric scattering of light (SPS) is one of the nonlinear optics processes which the most striking quantum properties which opens up wide possibilities for experimentally studying the quantum characteristics of electromagnetic radiation. In particular, the direct connection between the intensity of the radiation arising in SPS and the zero-point fluctuations of the electromagnetic field (ZF) can be used to study the effect of the optical density of the medium and the presence of boundaries with a finite magnitude of the reflection coefficient on the ZF.

In this paper we consider the manifestation in the SPS spectrum of the interference of the ZF in a plane-parallel layer and its effect on the coherent properties of the scattered field. We determine the conditions for experimentally observing the interference of ZF. A consistent consideration of the effect of boundaries on the ZF can be given only by the direct quantization of the field in an absorbing layer of finite thickness with semitransparent walls. The results described below are obtained by solving this problem on the basis of the generalized Kirchhoff law formulated by Klyshko[1] in terms of the scattering matrix.

The elementary SPS process is the annihilation of a photon in a pumping field mode with frequency ω_3 and wave vector k_3 with the simultaneous appearance of photons in two parametrically coupled modes with frequencies ω_1 and ω_2 and wave vectors k_1 and k_2. The parametric coupling of the modes means that the conditions $\omega_1 + \omega_2 = \omega_3$; $k_1 + k_2 + \Delta = k_3$ are satisfied. The wave mismatch Δ is connected with the finite thickness of the scattering layer l or with the finite magnitude of the coherence length l_{coh}.[2]

When emerging from the layer, the radiation fills a broad set of modes and forms a spectrum of the scattering intensity distribution (number of photons in a field mode) with a complicated structure. The appearance of photons in the signal field mode (ω_1, k_1) when emerging from the medium is possible only when in a medium with a non-vanishing quadratic polarizability there are present not only photons in the pumping mode (ω_3, k_3) but also photons in the intermediate mode (ω_2, k_2). In the case of a medium which is transparent to all frequencies ω_i at room temperature of the surrounding space, the presence of photons in the intermediate modes can be guaranteed only through the action of quantum fluctuations in the field whose magnitude in the visible and near IR bands exceeds thermal fluctuations by many orders of magnitude. SPS can thus be considered to be a process where light is scattered by the quantum fluctuations of the field with an effective action equivalent to the action of a field with a population of 1 photon in each mode which is uniform in frequency and space.

The number of photons $N_1(\omega_1, \theta_1)$ in the modes (ω_1, k_1), on emerging from the medium (θ_1 is the angle between k_1 and k_3 in the fixed plane of the triangle of the wave synchronism $k_1 + k_2 = k_3$), when there is no absorption and no reflection at the boundaries of the layer, has a functional form which is characteristic for nonlinear optics parametric processes[2]:

$$N_1(\omega_1, \theta_1) \sim g(\alpha_i, \delta_i, l) = \mathrm{sinc}^2(\Delta l/2). \tag{1}$$

Here $\Delta = \delta_3 - \delta_1 - \delta_2$ and δ_i is the component of k_i along the direction $k_3/|k_3|$. The presence of absorption and of reflection at the boundaries changes the shape of the form factor $g(\alpha, \delta, l)$ significantly.[3] In general, $g(\alpha, \delta, l)$ is rather complicated, but for the experimentally easily realizable situation of a negligible absorption the form factor takes the following form at all three frequencies:

$$g(\Delta, l) = (1 - R_1)(1 - R_2)\,\mathrm{sinc}^2(\Delta l/2)\,\frac{1}{D_1 D_2 D_3}[1 + R_2 + R_1 R_2 R_3 \tag{2}$$
$$- 4 r_1 r_2 r_3 \cos l(\delta_1 + \delta_2)\cos(l\delta_2)].$$

Here $R_i = r_i^2$, r_i is the amplitude coefficient for the reflection from the boundaries of the scattering layer, and $D_i = 1 - 2R_i \cos 2\delta_i l + R_i^2$ is the Airy function describing the interference of a plane wave of frequency ω_i in a plane-parallel layer. The presence of reflection leads to the appearance of a periodic modulation of the original contour (1) with three different periods determined by the interference of waves with frequencies ω_1, ω_2, and ω_3. Figure 1 shows the corresponding spectral line shape.

To observe the interference of the ZF, it is necessary to exclude the effect on the line shape of the signal radiation of the interference at the frequencies ω_1 and ω_3. This can be realized by plotting the transmitting layers in such a way that $R_1 \approx R_3 \approx 0$. In that case (2) takes the form

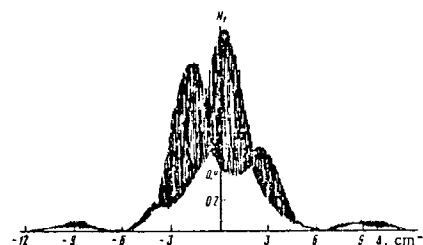$$g(\Delta, l, R_2) = (1 - R_2^2)\,\mathrm{sinc}^2\left(\frac{\Delta l}{2}\right)\frac{1}{D_2}. \tag{3}$$

FIG. 1. Spectral dependence of the normalized line shape of scattered radiation when all interacting waves are reflected ($R_1, R_2, R_3 \neq 0$).
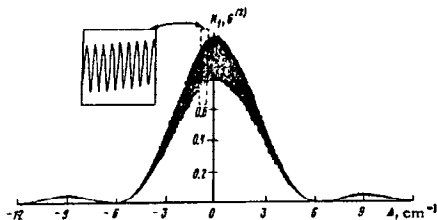
FIG. 2. Spectral dependence of the normalized line shape and of the correlation function of scattered radiation in the case when only waves at a frequency ω_2 are reflected ($R_1, R_3 = 0, R_2 \neq 0$).

The line shape corresponding to (3) is shown in Fig. 2. It is clear that even when there is no reflection at the frequency ω_1, the line shape of the signal radiation is represented by the function $\text{sinc}^2(\Delta l/2)$ with a modulated contour. The modulation in this case is determined by interference at the frequency ω_2. The fact that the coefficient F of the parametric conversion from the idler mode (ω_2, k_2) into the signal mode is small ($F \sim 10^{-7} \ldots 10^{-9}$) excludes a significant effect of the radiation, which is produced in the SPS process at the frequency ω_2, on the formation of the signal spectrum.

The change in the photon number distribution in the signal field modes (the appearance of an additional modulation of the line contour) when there is reflection present at the idler field frequency as compared to the case of non-reflecting boundaries is connected with the change in the luminance in the idler modes. The presence of semi-transparent boundaries of the scattering layer leads to the occurrence of interference of the idler modes and, as a consequence, to a redistribution of the density of states of the ZF in those modes. This in turn leads to the corresponding redistribution of the number of photons in the signal field modes which appear in the SPS process.

One can study the interference of the ZF not only in its dependence on the spectral line shape of the signal

radiation on the presence and magnitude of reflection at the idler field frequency but also in the change of one of basic coherent properties of scattered radiation — the hy classical space-time photon bunching.[1] The Glauber sec ond-order correlation function, which describes the coherent properties of the SPS, $G^{(2)} = \langle a_1^+ a_2^+ a_1 a_2 \rangle$, where a_i^+, a_i are the operators for creating or annihilating phot in the modes i, changes its form in the presence of a reflection. The change in form of the correlation function the appearance of an additional modulation of the contour requires that some well-defined conditions to be imposed on the radiation receiver be satisfied. The input apertur of the receiving devices must be much larger than the spectral and angular line widths of the SPS in order to measure the integral properties of the radiation over ma modes. Otherwise the input apertures must be much sma ler than the modulation period connected with the interference of the ZF. The coherent properties of a few mod can be measured in this case. The results of these measurements reveal the presence of the ZF interference.

To observe with certainty the ZF interference and the resolution of the modulated structure of the line shape and of the correlation function, connected with the ZF interference, the thickness of the scattering layer must not be greater than a few microns. In that case the frequency separation between two neighboring maxima will be of the order of 1 cm^{-1} and the flux density of the photons that form one maximum will be of the order of 10^2-10^3 s^{-1}.

[1]D. N. Klyshko, Photons and Nonlinear Optics [in Russian], Nauka, Mosc (1980).
[2]S. A. Akhmanov and R. V. Khokhlov, Nonlinear Optics, Gordon and Brea New York (1972).
[3]G. Kh. Kitaeva, D. N. Klyshko, and I. V. Taubin, Kvantovaya Elektron. (Moscow) 9, 560 (1982) [Sov. J. Quantum Electron. 12, 333 (1982)].

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