Possibility of simple and effective suppression of quantum amplitude fluctuations of light

A. V. Belinskiĭ
M. V. Lomonosov Moscow State University

(Submitted 6 February 1990)
Pis'ma Zh. Eksp. Teor. Fiz. **51**, No. 7, 341–343 (10 April 1990)

A comparatively simple possibility for preparing quantum fields with sub-Poisson photon statistics is proposed. The dispersion of the quantum intensity fluctuations can be suppressed by more than an order of magnitude in comparison with coherent light.

Hopes for solving several fundamental and applied problems of contemporary physics are pinned on quantum states of light in which the fluctuations of one of the quadrature components are suppressed with respect to vacuum: squeezed states. Some of the possibilities here concern attempts to observe gravitational waves. There are real possibilities for improving the limiting accuracy of several measurement systems. The promising outlook stems from a remarkable property of these quantum states: a lowering of the level of detection shot noise. Until recently, this noise level had been regarded as an unavoidable noise threshold in photodetection. Light with depressed quantum amplitude fluctuations is a particular case of squeezed states. It has the advantage that shot noise can be suppressed during direct photodetection. So far, the experimental progress achieved by the researchers dealing with these questions has been quite modest: The reduction of the noise level has so far not exceeded a factor of two.[1–5] Apparently one reason for this situation is that the existing methods for preparing sub-Poisson fields are complicated and not sufficiently effective.[1–10] In the present letter we are reporting an attempt to overcome these deficiencies.

Let us examine Fig. 1. Single-mode light with a plane wavefront in a coherent state $|\alpha_0\rangle$ overcomes the interface between two insulators. The first insulator is linear, while the second has a cubic real nonlinearity characterized by a coefficient $\chi^{(3)}$. The refractive index of the second insulator, n_2, is higher than that of the first under the working conditions. As the light intensity is increased, n_2 rises, while the transmission coefficient of the interface decreases. The system thus reaches a saturation, which results in a stabilization of the intensity. We will show that this stabilization also extends to quantum fluctuations. In the Heisenberg picture, the photon annihilation operator a corresponding to the surmounting of the interface by the light is $a = \tau a_0 + R a_v$, where the operator a_0 corresponds to the original coherent wave ($a_0 |\alpha_0\rangle = \alpha_0 |\alpha_0\rangle$), a_v corresponds to the vacuum state $|0\rangle$, and τ and R are amplitude transmission and reflection coefficients, which satisfy $\tau^2 + R^2 = 1$. If the light is sufficiently intense, and the relation $\overline{N}^2 \gg \Delta \overline{N^2}$, holds, where $N = a^+ a$ is the photon number operator, and $\Delta N = N - \overline{N}$ is the fluctuating part of this operator ($\overline{N} = \langle \alpha_0 | \langle 0 | a^+ a | 0 \rangle | \alpha_0 \rangle$), and also under the assumption that the nonlinear response of the medium is instantaneous, we can linearize the N dependence of τ with respect to fluctuations: $\tau \approx \bar{\tau} + (d\bar{\tau}/d\overline{N})\Delta N$, where $d\bar{\tau}/d\overline{N} = (d\bar{\tau}/d\bar{n}_2)(d\bar{n}_2/d\overline{N}) = \chi^{(3)} d\bar{\tau}/d\bar{n}_2$.

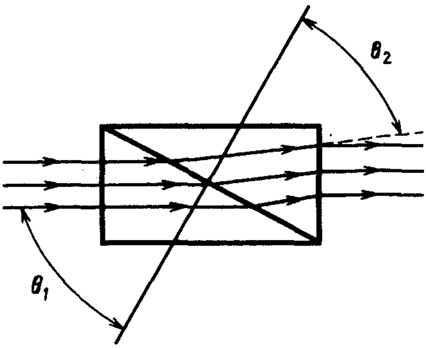

FIG. 1.

We write a as $a = (\bar{a} + \Delta a)e^{-i\Delta\Phi}$, where Δa and $\Delta\Phi$ are the fluctuation components of the amplitude and phase. Under the condition $N \gg 1$, both operators (Δa and $\Delta\Phi$) are Hermitian. The consant phase is set equal to zero. We then have

$$(\bar{a} + \Delta a)e^{-i\Delta\Phi} = \{[\bar{\tau} + 2(d\bar{\tau}/d\bar{N})\bar{a}\Delta a](\alpha_0 + \Delta a_0) + Ra_v\}e^{-i\Delta\varphi}. \quad (1)$$

The nonlinear phase modulation $\Delta\varphi = \chi^{(3)} l \Delta N$, which arises during the propagation of light over a distance l in a second insulator, has been taken into account here. We have also assumed $a_0 = \alpha_0 + \Delta a_0$ and $\Delta N \approx 2\bar{a}\Delta a$. Singling out the real parts of (1), and retaining only the terms which are linear in the fluctuations, we find

$$\Delta a = [\bar{\tau}(\Delta a_0' + \Delta a_0'^{+}) + \bar{R}(a_v' + a_v'^{+})]/2(1 - 2\chi^{(3)}\bar{N}\bar{\tau}^{-1}d\bar{\tau}/d\bar{n}_2), \quad \bar{a} = \bar{\tau}\bar{a}_0, \quad (2)$$

where $\Delta a_0'$ and a_v' differ from Δa_0 and a_v by the phase factor $e^{i(\Delta\Phi - \Delta\varphi)}$. The dispersion of the fluctuations of the number of photons is $\Delta\overline{N^2} \approx 4\bar{N}\,\overline{\Delta a^2}$. The Fano factor $F = \Delta\overline{N^2}/\bar{N}$, which characterizes the degree of suppression of the quantum intensity fluctuations with respect to coherent light, is

$$F = [1 + \chi^{(3)}\bar{N}\sin(\theta_1 - \theta_2)/\bar{n}_2\cos^2\theta_2\sin(\theta_1 + \theta_2)]^{-2}. \quad (3)$$

Here we have used[11] $R = \sin(\theta_1 - \theta_2)/\sin(\theta_1 + \theta_2)$. Strictly speaking, in calculating the dispersion we should have also retained the terms which are quadratic in the fluctuations from the outset, but when the average is taken, they contribute nothing to the final expressions. According to (3), the optimum suppression of quantum noise can be achieved at small values of $\bar{n}_2 - \bar{n}_1$ and at angles of incidence θ_1 near grazing incidence. If we choose the second insulator to be semiconductor (InSb or CdS) or a liquid-crystal structure in a narrow layer between two linear materials in the prism shown in Fig. 1 (the refractive index of the second insulator must be equal to that of the liquid crystal), then values[10,12,13] $\chi^{(3)}\bar{N} \approx 0.1$ could be attained easily, even in cw operation. With $\bar{n}_1 = 1.5$, $\bar{n}_2 = 1.51$, and $\theta_1 = 88°$, we find $F \approx 0.008$. In other words, the quantum intensity fluctuations can be suppressed by more than an order of magnitude. Since the rise time of the nonlinear response of the medium, T_{non}, is nonzero, this effect will be observed in a frequency band with an upper bound T_{non}^{-1}.

[1]D. F. Smirnov and A. S. Troshin, Usp. Fiz. Nauk **153**, 233 (1987) [Sov. Phys. Usp. **30**, 851 (1987)].
[2]Special issues: J. Mod. Opt. **34**, No. 6/7, 1987; J. Opt. Soc. Am. B **4**, No. 10, 1987.
[3]M. C. Teich and B. E. A. Saleh, *Progress in Optics* (ed. E. Wolf), Vol. **24**, Elsevier Science Publ., Amsterdam, 1988, p. 1.
[4]Y. Yamamoto *et al.*, Phys. Rev. A **34**, 4025 (1986).
[5]Y. Yamamoto *et al.*, Phys. Rev. A **33**, 3243 (1986).
[6]Yu. M. Golubeu and I. V. Sokolov, Zh. Eksp. Teor. Fiz. **87**, 408 (1984) [Sov. Phys. JETP **60**, 234 (1984)].
[7]H. A. Haus and Y. Yamamoto, Phys. Rev. A **34**, 270 (1986).
[8]A. V. Belinskiĭ and A. S. Chirkin, Pis'ma Zh. Tekh. Fiz. **15**, No. 10, 84 (1989 [Sov. Tech. Phys. Lett. **15**, 408 (1989)].
[9]A. V. Belinskiĭ and A. S. Chirkin, Kvant. Elektron. (Moscow) **16**, 889 (1989) [Sov. J. Quantum Electron. **19**, 579 (1989)].
[10]K. Watanabe *et al.*, Phys. Rev. Lett. **62**, 2257 (1989).
[11]M. Born and E. Wolf, *Principles of Optics*, Pergamon, New York, 1959.
[12]S. A. Akhmanov *et al.*, *Optics of Femotosecond Laser Pulses*, Nauka, Moscow, 1988, p. 70.
[13]S. M. Arakelyan and Yu. S. Chilingaryan, *Nonlinear Optics of Liquid Crystals*, Nauka, Moscow, 1984, p. 118.

Translated by Dave Parsons