Phase conjugation of single photons

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The possibility of conjugation of a four-wave hypersonic reversing mirror based on the Brillouin effect with a quantum amplifier operating in the two-pass regime is investigated with an aim at minimizing the quantum noise that limits the sensitivity of reversing mirrors. Phase conjugation (PC) of a single-mode single-frequency pulsed light signal of energy $4\cdot 10^{-17}$ J is achieved in experiment. The condition of PC-noise superluminescence of an amplifier is ascertained and the sensitivity limit of the investigated system is estimated. It is demonstrated experimentally that at unity signal/noise ratio the energy level of the input signal for which PC is feasible corresponds to 30 photons per transverse mode.

The present paper is devoted to an investigation of the feasibility of phase conjugation (PC) of weak optical fields. This question was previously considered in Refs. 1–3. The values obtained there, however, for the minimum energy $W_{\min}$ of a signal whose wave front can be reversed were limited by the thermal noise in the nonlinear medium. Here, on the contrary, we consider ways of lowering $W_{\min}$ down to values limited only by the quantum properties of the light fields.

Under PC experimental conditions typical of nonlinear optics, a weak signal wave interacts with one of the high-power pumps via four-wave mixing. This results in spatially inhomogeneous perturbations of the refractive index of the medium Ω. Scattering of an opposite pump signal by these perturbations produces the reverse wave. Excitation of refractive-index perturbation leads to PC only if the strong-pump photon decay is initiate principally by the priming photons of the signal wave, and not by the random thermal phonons responsible for the density fluctuations $\Delta\rho$ of the medium. To this end, obviously, the number of signal-wave priming photons concentrated in one spatial-temporal mode should exceed the corresponding number $\bar{n} = 1/\exp[(\hbar\Omega/kT) - 1] \approx kT/\hbar\Omega$ of the thermal phonons in the equilibrium distribution of the density fluctuations (here T is the absolute temperature of the medium, $\hbar$ and k are respectively the Planck and Boltzmann constants, and Ω is the phonon frequency). Usually $\bar{n}$ exceeds 10^3.

We recognize now that PC of a wave with a stationary wavefront is due to scattering of the pump waves by some single spatial (transverse) mode in the $\Delta\rho$ distribution. On the other hand, the number of temporal (longitudinal) modes in the $\Delta\rho$ distribution can in general be quite large. This number is determined by the product of the characteristic interaction time τ (the duration of the scattered pulse under unsaturated gain conditions) by the width $\Delta\omega$ of the frequency spectrum of the thermal phonons that cause the scattering into the required transverse mode. At a finite value of $\Delta\omega$ the total number $\bar{n}\Delta\omega\tau$ of the thermal phonons that cause scattering into some mode should be less than the total number $W/\hbar\omega$ of the photons, or

$$W > W_{min} \approx \hbar\omega\bar{n}\Delta\omega\tau.$$

This equation was obtained in Refs. 1 and 2. It was shown experimentally in Refs. 2 and 3 that under optimal conditions it is possible to realize, at a wavelength $\lambda = 1.06$ μm, PC of a signal wave of energy $W_s \approx 10^{-14}$ J, which differs by only several times from the indicated limiting value.

The thermal limit $W_{\min}$ can be lowered by first amplifying the lower-energy signal wave to make the number of phonons it contains, on impinging on the phase-conjugating mirror, larger than the total number of thermal phonons in the corresponding transverse mode. Amplification, however, mixes the signal with the superluminescent quantum-amplifier noise whose value, referred to the input, is approximately one photon per mode. At a gain $k_a > \bar{n}$ it is just the superluminescence noise reflected from the reversing mirror in its band $\Delta\omega$ which should limit the minimum signal energy input to the amplifier to

$$W_{min} \approx \hbar\omega\Delta\omega\tau.$$

To reach the quantum limit for a minimum signal energy subject to PC, we investigate below the possibility of combining into one system a four-wave hypersonic reversing mirror and a quantum amplifier operating in the two-pass regime (at $\lambda = 1.06$ μm). In the first part of the paper we determine the conditions for phase conjugation of the luminescent-amplifier noise and estimate the sensitivity limit of the investigated system.

Experiments reported in the second part show that at unity signal/noise ratio the input-signal energy level at which phase conjugation is feasible corresponds in principle to 30 photons per transverse mode.

I. NOISE IN AN AMPLIFIER + REVERSING MIRROR SYSTEM

If a quantum amplifier is located in front of the reversing mirror, it is necessary to separate three additive components of the noise radiation.

1. Intrinsic reversing-mirror noise amplified in one pass by the quantum amplifier. This noise depends on the specific form of the reversing mirror. We have investigated a four-wave hypersonic reversing mirror based on the Brillouin effect.[4–7] The noise source of such a mirror under optimal experimental conditions[2,8] is the backscattering of the high-power pump pulse by thermal phonons near the exit end of the cell with the nonlinear medium. High reflection coefficients R of this mirror are obtained in the absolute-instability regime, which is characterized by an exponential

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growth of the reversed-wave power with time and accordingly by a number of noise radiation longitudinal modes close to unity, $\Delta\omega\tau\sim 1$. In this regime, the PC-mirror noise energy per transverse mode, after passage of the radiation to the quantum amplifier, can be estimated from the relation

$$W_1\approx\hbar\omega\bar{n}k_aR, \qquad (1)$$

where k_a is the gain of the quantum amplifier. In the absolute-instability regime the noise radiated by a PC mirror is, in contrast to the superluminescence noise of a quantum amplifier, spatially coherent, i.e., it has a clearly pronounced speckle-inhomogeneous transverse field structure.

2. Noise originating at the input of the quantum amplifier, amplified in a frequency band and then reflected by the PC mirror and again amplified on returning through the amplifier. This can be called two-pass noise. The amplifier bandwidth $\Delta\omega_a$ usually exceeds significantly the bandwidth of the PC mirror, and each component of the superluminescence noise propagating in the angle seen by the PC mirror is reflected from it with its spectrum narrowed down. If the PC takes place in the absolute instability regime, the reflected superluminescence-radiation has different statistics as a result of the narrowing of the frequency spectrum and the decrease of the pulse duration, and becomes spatially coherent, so that $\Delta\omega\tau\sim 1$. In the return pass through the amplifier this radiation has a speckle-inhomogeneous transverse field structure. The two-pass noise energy per transverse mode (or resolution element) is given in this case approximately by

$$W_2\approx\hbar\omega k_a^2R. \qquad (2)$$

3. Broadband single-pass superluminescence noise starting from the amplifier side facing the PC mirror and increasing in the propagation direction of the reversed wave. The energy of this noise per transverse mode is

$$W_3\approx\hbar\omega k_a\Delta\omega_a\tau_a, \qquad (3)$$

where $\Delta\omega_a\tau_a$ is the number of longitudinal modes in the noise and τ_a is the duration of the one-pass superluminescence pulse. Since the noise is amplified by an ordinary rather than a superregenerative quantum amplifier, the one-pass noise is statistially incoherent. The speckle-inhomogeneous transverse structure of this radiation changes in a characteristic time $1/\Delta\omega_a$. Therefore in a registration time substantially longer than $1/\Delta\omega_a$ the transverse distribution of the energy density w of the one-pass noise becomes uniform without prominent bright spots.

To describe the relative contribution of each of the spontaneous noise components we introduce their normalized values

$$\varkappa_1=\frac{W_1}{W_3}\approx\frac{\bar{n}R}{\Delta\omega_a\tau_a},\quad \varkappa_2=\frac{W_2}{W_3}\approx\frac{k_aR}{\Delta\omega_a\tau_a}. \qquad (4)$$

The values of $\varkappa_1$ and $\varkappa_2$ can be measured by determining the fluctuation level in the transverse distribution of the total energy density of the amplified noise radiation leaving the system. It is convenient to describe this level by the variance

$$V=[\langle(w-\langle w\rangle)^2\rangle]^{1/2}/\langle w\rangle, \qquad (5)$$

where the angle brackets denote averaging over the transverse coordinates. We recognize the the noise energy density w can be expressed in terms of the sum of the energy densities of the three indicated noise types: $w=w_1+w_2+w_3$. We note, in addition, that there are no fluctuations in the incoherent emission of one-pass noise and that

$$\langle(w_3-\langle w_3\rangle)^2\rangle=0. \qquad (6)$$

Recognizing that the thermal phonons from which the light waves in the phase-conjugating mirror are scattered have a normal distribution, we assume that the fluctuations in the speckle-inhomogeneous spatially coherent noise of a phase-conjugating mirror and in two-pass superluminescence noise also have a normal distribution for which

$$\langle(w_{1,2}-\langle w_{1,2}\rangle)^2\rangle\approx\langle w_{1,2}\rangle^2.$$

Since the relative values $\langle w\rangle/\langle w_2\rangle$ and $\langle w_2\rangle/\langle w_3\rangle$ coincide with $\varkappa_1$ and $\varkappa_2$, it is easy to obtain for them respectively the values 0.54 and 1.7 in experiment and -0.88 and 1.6 theoretically.

The foregoing estimates show that under the experimental conditions the decisive noise component is two-pass noise whose energy exceeds that of the other components. The approximate agreement between the theoretical and experimental results confirms that the model premises advanced here describe adequately the properties of the observed noise.

To conclude this section, we estimate the minimum number $n_{\min}$ of photons in a signal wave whose PC can be recorded in principle in the investigated system. Assuming unity ratio of the input-signal and total energies, we determine the average number of all the noise photons per transverse mode: $n_{\min}\approx 1+1/\varkappa_1+1/\varkappa_2$. The theoretical value is

$$n_{\min}^{\text{theor}}\approx[\Delta\omega_a\tau_a+R(\bar{n}+k_a)]/k_aR. \qquad (7)$$

Using the above data, we obtain $n_{\min}^{\text{theor}}=2$. Consequently, the results point to the feasibility, in principle, of reaching the quantum limit in phase conjugation of a weak signal.

II. PHASE CONJUGATION OF QUANTIZED FIELDS

The minimum energy of a one-mode light signal whose PC can be recorded against a noise background depends on two types of factors, which can be arbitrarily called technical and natural. The former are connected with the experimental conditions, and the latter with the fundamental constraints imposed by the quantized character of the light fields and by the physical processes on which the PC phenomenon is based. The joint action of the natural factors was investigated above. The influence of the technical factor is minimized by an optimal choice of the experimental setup and operating conditions. This calls for matching the spacial and temporal parameters of the PC signal wave to the parameters of the pulses of the pumps, eliminating of self-excitation of the PC mirrors as well as of the amplifier, and preventing the opposing pump waves from directly interacting in the PC-mirror medium and from penetrating into the amplifier. We monitored the satisfaction of each of the foregoing conditions under the conditions of our experiment, and were therefore able to obtain PC of a signal wave of energy $W_c\approx 4\cdot 10^{-17}$ J. Figure 1 shows the two-dimensional distributions of the energy density in a phase-conjugated wave at input signal energies $W_c\approx 2\cdot 10^{-13}$ J (Fig. 1a) and

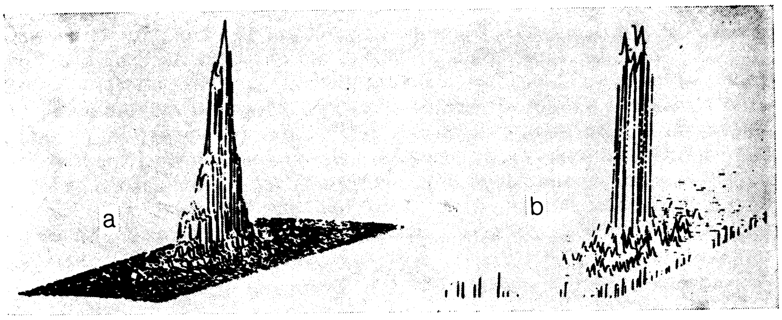

FIG. 1. Transverse distribution of the energy density in a reversed wave at input signal energies $W_c \approx 2\cdot 10^{-13}$ J (a) and $W_c \approx 4\cdot 10^{-17}$ J (b).

$W_c \approx 4\cdot 10^{-17}$ J (Fig. 1b). Analysis has verified the good agreement (within 20%) of their characteristic widths measured at a height e^{-1} of the maximum. The relative noise level corresponding to a strong input signal (see Fig. 1a) is substantially lower than that for a $4\cdot 10^{-17}$ J signal (Fig. 1b). The maximum energy density of the phase-conjugated wave in Fig. 1b is approximately 7 times the background due to the noise radiation.

It can be concluded on this basis that the minimum energy density of the reversed wave becomes comparable with the noise background at an input-signal energy $W_c^{\exp} \approx 6\cdot 10^{-18}$. This means that the PC of a signal wave containing approximately $n_{\min}^{\exp} \approx 30$ photons can in principle be recorded at unity signal/noise ratio.

The disparity between the expected (from the results of Sec. II) and the experimental values of $n_{\min}$ is apparently due to the joint influence of the aforementioned technical factors, particularly to the small difference between the signal frequency and the frequency at which the most appreciable noise amplification takes place.

[1]V. I. Bespalov and G. A. Pasmanik, Nonlinear Optics and Adaptive Laser Systems [in Russian], Nauka, 1986.
[2]V. I. Bespalov, A. Z. Matveev, and G. A. Pasmanik, Izv. Vussh. Ucheb. Zav. Radiofizika **29**, 1080 (1986).
[3]N. F. Andreev, V. I. Bespalov, M. A. Dvoretsky, *et al.* Rev. Roum. Phys. **31**, 951 (1986).
[4]N. F. Andreev, V. I. Bespalov, A. A. Kiselev, *et al.*, Pis'ma Zh. Eksp. Teor. Fiz. **32**, 639 (1980) [JETP Lett. **32**, 625 (1980)].
[5]N. F. Andreev, V. I. Bespalov, M. A. Dvoretskiĭ, and G. A. Pasmanik, Kvantovaya Elektron. (Moscow) **11**, 1476 (1984) [Sov. J. Quant. Electron. **14**, 999 (1986)].
[6]M. Z. Hazzel and A. M. Scott, IEEE J. Quant. Electron. **22**, 1248 (1986).
[7]M. D. Skeldom, P. Narum, and R. W. Boyd, Opt. Lett. **12**, 342 (1987).
[8]E. L. Bubis, 0. V. Kulagin, G. A.Pasmanik, and A. A. Shilov, Kvantovaya Elektron. (Moscow) 11, 1211 (1984) Sov. J. Quant. Electron. **14**, 815 (1984)].

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