Absolute instability of oppositely directed waves without a frequency detuning

I. Yu. Anikeev, D. A. Glazkov, I. G. Zubarev, and S. I. Mikhailov
P. N. Lebedev Physics Institute, Academy of Sciences of the USSR, Moscow

(Submitted 2 November 1988)
Pis'ma Zh. Eksp. Teor. Fiz. **48**, No. 11, 593–597 (10 December 1988)

For the first time, an absolute instability and high reflection coefficients, 5×10^6 at an input-signal energy of 10^{-10} J, have been achieved at a zero frequency detuning. Two regimes of an absolute instability of the interacting waves have been observed: with and without the application of an external signal.

Four-wave mixing processes are widely used in experiments on optical phase conjugation. The use of the Brillouin (or "Mandel'shtam-Brillouin") nonlinearity for this purpose has made possible phase conjugation with the highest signal reflection coefficient which has been achieved in experiments of this type, $\sim7\times10^5$ (Ref. 1). It turns out that such high reflection coefficients stem from an absolute instability of the interacting waves.[2,3] The absolute instability regime is achieved only at certain values of the growth rates of these waves in the field of the oppositely directed pump reference waves. These growth rates are at a minimum when there is a wave "detuning."[3] Before now, the regime of an absolute instability of the waves and the optimum wave detuning have been achieved successfully only when there has been a *frequency* detuning of the oppositely directed reference waves,[3] i.e., only when the difference between their frequencies $(\omega_0^+ - \omega_0^-)$ has not been equal to the Brillouin shift for the active medium, Ω:

$$\omega_0^+ - \omega_0^- \neq \Omega .$$

If the frequency detuning of the waves is zero, two factors act to prevent the attainment of a regime in which the oppositely directed pump and Stokes-signal waves decay and thus to prevent the attainment of high reflection coefficients in weak-signal phase-conjugation systems: the relatively high threshold for the absolute instability[2,3] and the parasitic pumping of energy from the pump reference wave to the Stokes reference wave due to the inadequate polarization decoupling of these waves.[4,5] It is for this reason that the absolute instability has not previously been seen experimentally at a zero frequency detuning, and the reflection coefficients for the external signal which have been achieved have not exceeded 20 (Ref. 4). In the present study we have succeeded in achieving a regime of an absolute instability of the waves during four-wave mixing with a zero frequency detuning of the waves, under the condition

$$\omega_0^+ - \omega_0^- = \Omega .$$

A theoretical analysis and also experiments have shown that the wave detuning which is required can be achieved by arranging an angular detuning of the oppositely directed reference pump waves.

In order to achieve a regime of an absolute instability, it is necessary to arrange conditions such that the oppositely directed reference pump waves do not interact with each other directly in the active medium. If there is no frequency detuning of the waves for a Brillouin nonlinearity, these waves can be detuned only in terms of polarization.

In order to improve the polarization detuning of the reference wave in the present study, we used an independent source of a Stokes reference wave, whose output was passed through a Glan-Thomson prism crossed with the polarization plane of the pump light. On the one hand, this approach sharply improved the quality of the detuning; on the other, it introduced the posslbility of varying the direction alomg which the Stokes wave was coupled in with respect to the oppositely directed pump wave. In our case the detuning of the waves is given by the expression

$$\Delta k = \Delta k_{\text{freq}} + \Delta k_{\text{spat}} = (\omega_0^+ + \omega_1^- - \omega_0^- - \omega_1^+)/v_0 - k\,\vec{\theta}_s \vec{\theta}_{\text{ref}}\,. \tag{1}$$

Here ω_0^+, ω_0^-, ω_1^- ω_1^+ are the frequencies of the interacting waves (Fig. 1); v_0 is the velocity of light in the active medium; k is the modulus of the wave vector; $\theta_s = k_{1\perp}^+/k$ is the vector angle between the direction of the pump reference wave and that of the signal wave; and $\theta_{\text{ref}} = k_{0\perp}^-/k$ is the vector angle by which the reference Stokes signal deviates from the direction exactly opposite the pump reference wave (Fig. 1). The frequency and spatial parts of Δk may cancel each other out if the frequencies and angles of the interacting waves are chosen appropriately. The derivation of (1) made use of the small value of the frequency shift between the interacting waves and the small values of the angles θ_s and θ_{ref}. Otherwise, the dynamic equations describing the situation in Fig. 1 are fully equivalent to those used in Refs. 2 and 3.

The absolute instability of the interacting waves can be observed in two ways: with or without the application of an external signal. Without an external signal, only the two oppositely directed reference pump waves are incident on the medium, and the "signal" and "conjugate" waves are excited in the medium in the course of the abso-

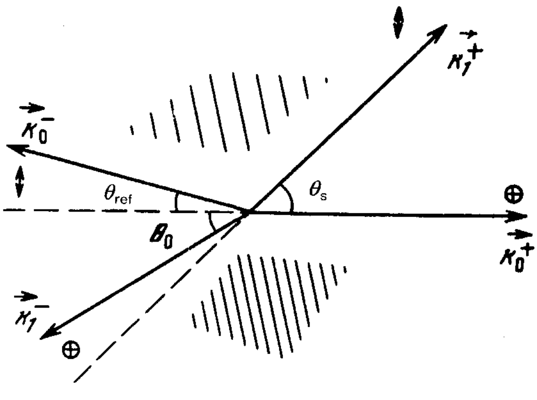

FIG. 1. Wave-vector diagram illustrating the four-wave mixing. $\mathbf{k}_1^\pm$ Wave vectors of the pump reference waves; $\mathbf{k}_1^+$ and $\mathbf{k}_1^-$ — wave vectors of the signal and conjugate waves.

lute instability (generation) from the spontaneous noise level. Experiments have been carried out both in a version of generation from spontaneous noise and in a version of phase conjugation of an external signal. The pump source was the single-mode, single-frequency output from a Nd:YAG laser with a pulse length of 30 ns at half-maximum

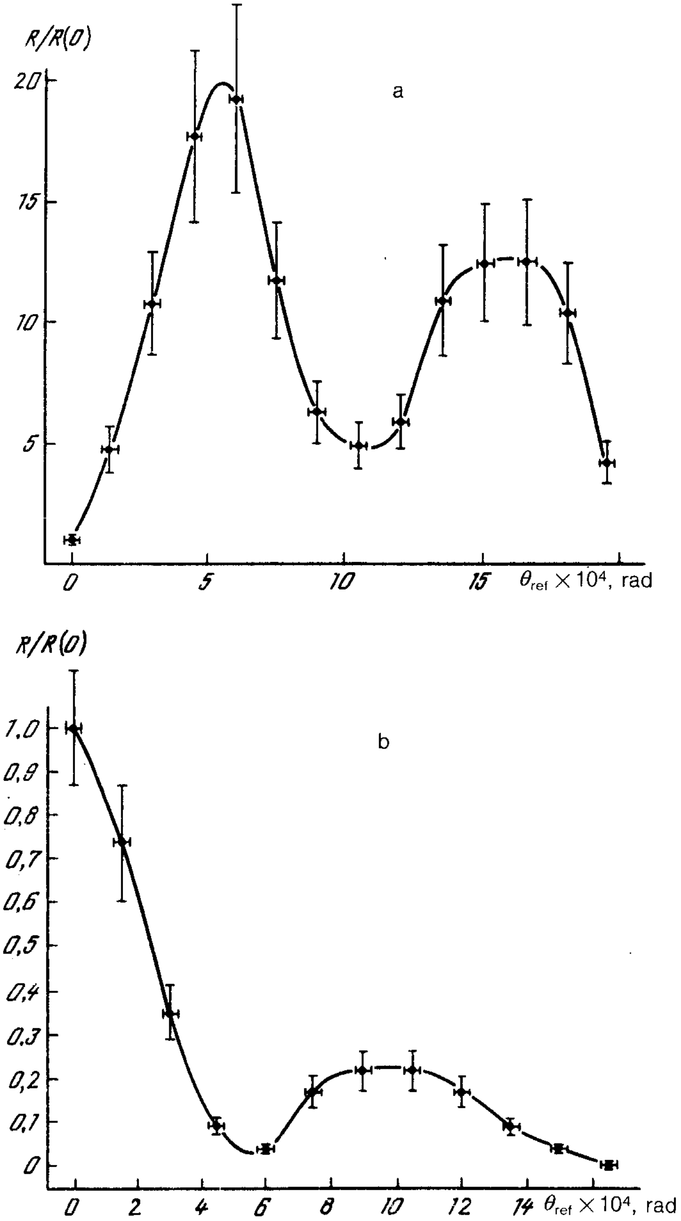

FIG. 2. The normalized reflection coefficient for the signal wave, $R/R(O)$, versus the angular detuning of the reference waves, θ_{ref}. a—Above the threshold for the absolute instability; b—below it.

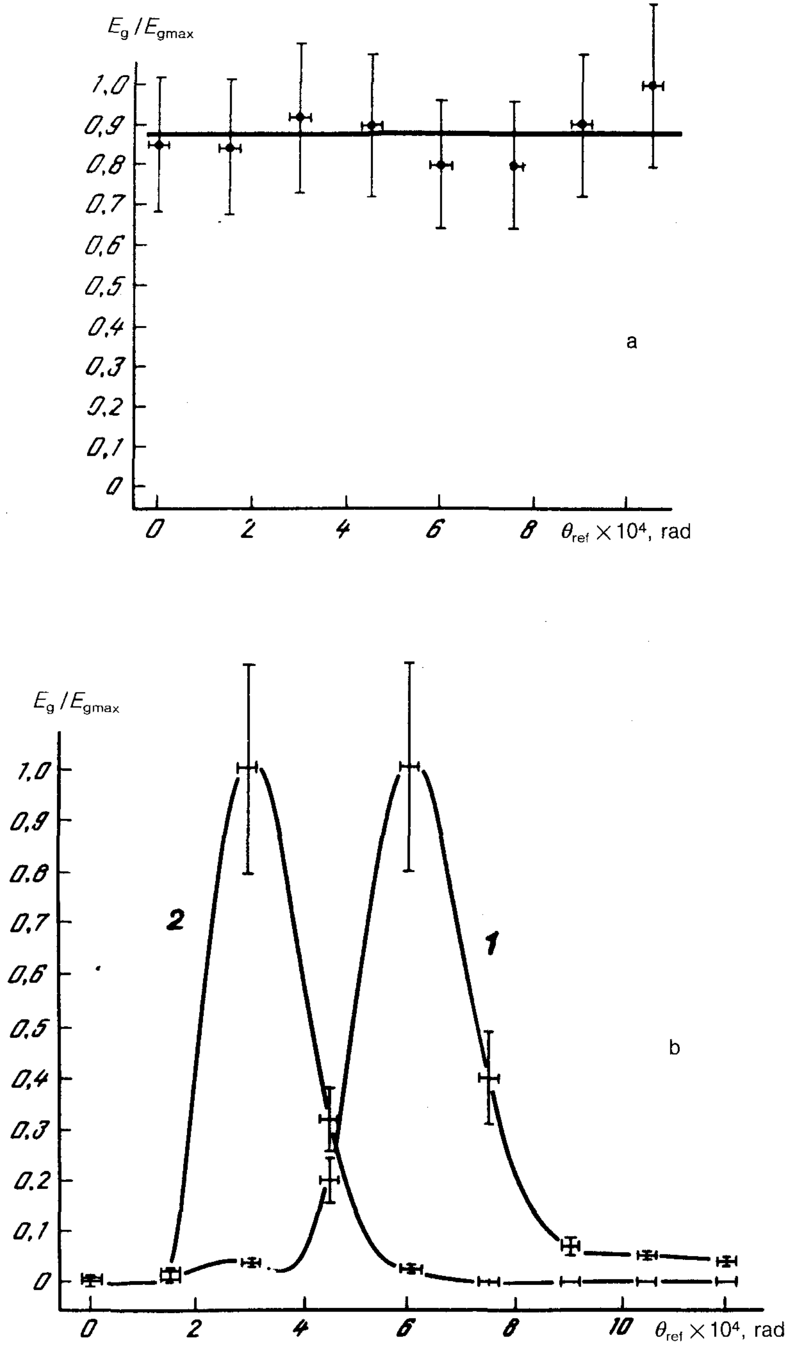

FIG. 3. Normalized generation energy during the decay of pump reference waves, E_g/E_{max}, versus their angular detuning θ_{ref}. a—The angular aperture of the receiving calorimeter is 5×10^{-2} rad; b—5×10^{-4} rad. 1) $\theta_0 = 0.8\times10^{-2}$ rad; 2) $\theta_0 = 1.6\times10^{-2}$ rad.

and an energy up to 100 mJ. As the reference Stokes wave we used part of the same light, inverted in an auxiliary cell with a polarization orthogonal with respect to that of the pump. The interacting waves were mixed in a cell 20 cm long. Each cell was filled with carbon bisulfide, so we have

$$\Delta k_{\text{freq}} = 0, \quad \Delta k = \Delta k_{\text{spat}} = -k \vec{\theta}_s \vec{\theta}_{\text{ref}} \,. \tag{2}$$

Figure 2 shows the reflection coefficient for the signal wave, normalized to the maximum value, versus the magnitude of the detuning of the waves for (a) a large growth rate, ~25, and (b) a small growth rate, ~1. Clearly, the angular deviation of the reference Stokes wave reduces the reflection coefficient in the case of small growth rates, while at large growth rates we observe, on the contrary, two maxima in this interval of the wave detuning. These two maxima correspond to minima of the thresholds for the absolute instability.[3] The maximum reflection coefficient for the signal wave which we achieved was 5×10^6 at an input-signal energy of 10^{-10} J.

Figure 3 shows corresponding results for the generation energy in the case of an absolute instability in the absence of an external signal. In case a) the angular aperture of the calorimeter was 5×10^{-2} rad, while in case b) it was 5×10^{-4} rad. In case b) the aperture of the calorimeter was oriented at angles $\theta_0 = 0.8\times10^{-2}$ and $\theta_0 = 1.6\times10^{-2}$ rad (Fig. 1). We clearly see that the generation energy collected over a wide monitoring angle is essentially independent of the angle between the reference waves, while in the case of a narrow monitoring angle the dependence is of a resonant nature. The optimum angle θ_{ref} is approximately inversely proportional to the angle θ_0. Under the condition $\theta_{\text{ref}} \gg \theta_0$, in which case we have $\theta_s = \theta_0 + \theta_{\text{ref}} \approx \theta_0$ (Fig. 1)—corresponding to our experimental situation—this result confirms relation (2). On the other hand, it indicates that the directional pattern of the light consists of two lobes, which make angles of $\theta_{\text{ref}} \pm \theta_s$ with the light in the pump reference wave; these angles correspond to the minimum of the instability threshold.

In summary, an absolute instability has been achieved at a zero frequency detuning for the first time, and high values of the weak-signal reflection coefficient, $\sim5\times10^6$, have been achieved, with a rotation of the directional pattern by θ_{ref} from the "exactly backward" direction. It has been shown that an angular detuning of the oppositely directed pump reference waves makes it possible to smoothly vary the wave detuning and to achieve an angular selectivity in the reflection of an external signal.

[1] N. F. Andreev, V. I. Bespalov, A. M. Kiselev *et al.*, Pis'ma Zh. Eksp. Teor. Fiz. **32**, 639 (1980) [JETP Lett. **32**, 625 (1980)].

[2] B. Ya. Zel'dovich and V. V. Shkunov, Kvant. Elektron. (Moscow) **9**, 393 (1982) [Sov. J. Quantum Electron. 12, 223 (1982)].

[3] N. F. Andreev, V. I. Bespalov, A. M. Kiselev *et al.*, Zh. Eksp. Teor. Fiz. **82**, 1047 (1982) [Sov. Phys. JETP **55**, 612 (1982)].

[4] E. L. Bubis, G. A. Pasmanik, and A. A. Shilov, Kvant. Elektron. (Moscow) **10**, 1488 (1983) [Sov. J. Quantum Electron. **13**, 971 (1983)].

[5] V. F. Efimokov, I. G. Zubarev, S. I. Mikhaĭlov *et al.*, Kvant. Elektron. (Moscow) **11**, 303 (1984) [Sov. J. Quantum Electron. **14**, 209 (1984)].

Translated by Dave Parsons