TWO-QUANTUM AMPLIFICATION OF A SHORT LIGHT PULSE

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1. It is known that the propagation of a powerful light pulse in an amplifying or an absorbing medium with single-quantum transitions has a nonlinear character, owing to the saturation of the level population. The dependence of the gain of the medium or of the transmission of a saturating filter on the radiation intensity makes it possible to obtain powerful short and ultrashort pulses of coherent light [1-4].

In this paper we propose to use for this purpose a nonlinearity of entirely different type - the nonlinearity of multiphoton processes. In particular, two-quantum transitions in a medium with inverted population lead to a nonlinearity of the gain even without saturation of the level population. When a powerful light pulse propagates in a medium in which gain is produced by the two-quantum transitions, the pulse width is very effectively reduced, since the coefficient of two-quantum amplification is proportional to the instantaneous pulse intensity.

We note that generation of emission with the aid of two-quantum transition was first considered by Prokhorov and Selivanenko [5] and by Sorokin and Braslau [6], but was never observed experimentally. It will be noted below that this method of amplification of ultrashort powerful pulses of light is much more convenient for the production of negative absorption via two-quantum transitions than the generation method.

2. Let a light pulse of frequency ω propagate in a medium with inverted population of two levels with energy difference $\Delta E = 2\hbar\omega$. We consider a case in which the pulse duration τ_p is much longer than the reciprocal of the spectral width of the transition $1/\Delta\omega$ ($\tau \gg \Delta\omega^{-1}$), and the pulse energy $\mathcal{E}$ is much smaller than the energy of population saturation due to the two-quantum transitions $\mathcal{E}_s$ ($\mathcal{E} \ll \mathcal{E}_s$). In this region, the mechanism of nonlinearity due to saturation is not effective. Then the change in the pulse intensity is described in the one-dimensional case by the equation

$$\frac{\partial P(\tau, x)}{\partial x} = P(\tau, x)\{\alpha[P(\tau, x)] - \gamma\}, \quad P(t, x) = \frac{c}{8\pi}E^2(t, x), \tag{1}$$

where $\tau = t - x/c$, c is the pulse velocity, $\alpha(P)$ is the gain per unit length due to the two-quantum transitions, and γ is the coefficient of linear loss per unit length. The two-quantum gain α is given by the expression [7,8]

$$\alpha(P) = \sigma(P)N = -4\pi\frac{\omega}{c}\chi''(\omega)E^2, \tag{2}$$

where $\sigma(P) = \sigma_1 P$ is the cross section of the two-quantum transition, N the density of the inverted population, and $\chi''(\omega)$ is the nonlinear susceptibility of the active particles at the frequency ω.

The solution of (1) is

$$P(x, \tau) = P_0(\tau) e^{-\gamma x}\{1 - \gamma^{-1} \alpha\, [P_0(\tau)](1 - e^{-\gamma x})\}^{-1}, \tag{3}$$

where $P_0(\tau) = P(x = 0, \tau)$ is the shape of the pulse at the boundary of the medium. If the maximum gain of the initial pulse, $\alpha_{0m} = \alpha(P_0(\tau_m))$ (τ_m is the point of maximum intensity), exceeds the loss γ, then the intensity of the pulse at the maximum becomes infinite at a certain distance

$$x_{cr} = \frac{1}{\gamma} \ln \frac{\alpha_{0m}}{\alpha_{0m} - \gamma} \quad (\alpha_{0m} > \gamma) \tag{4}$$

It can be shown that the pulse duration vanishes at the same point:

$$\tau_p = \tau_0[1 - \gamma^{-1} \alpha_{0m}(1 - e^{-\gamma x})]^{1/2}, \tag{5}$$

and the pulse energy $\mathcal{E} \approx \tau_m P(\tau_m)$ also increases without limit:

$$\mathcal{E} = \mathcal{E}_0\, e^{-\gamma x}[1 - \gamma^{-1}\alpha_{0m}(1 - e^{-\gamma x})]^{-1/2} = \mathcal{E}_0 e^{-\gamma x}\, \tau_0/\tau_p, \tag{6}$$

where τ_0 and $\mathcal{E}_0$ are the initial duration and energy of the pulse.

Relations (4) - (6) are valid until the nonlinearity mechanism due to saturation comes into play. In the population saturation region, the pulse width is reduced further, but now as a result of two nonlinearity mechanisms.

No total "collapse" of the pulse occurs, of course, since effects of nonlinear absorption due to multiquantum processes of higher order, dispersion of the refractive index, etc. come into play at high intensities ($\sim 10^{12}$ W/cm^2) and short durations ($\sim 10^{-13}$ sec). An analysis of the role of these effects requires a separate study. We note, however, that the limiting duration of ultrashort pulses is much smaller in this method than in a laser with self-phasing of the modes by nonlinear absorption [3,4], since the pulse duration does not depend here on the lifetime T_1 of the particles at the upper level.

3. For an experimental realization of the proposed method, it is most convenient to use an initial pulse of duration $\sim 10^{-11}$ sec and energy $\sim 10^{-3}$ - 10^{-2} J/cm^2, obtainable, say, from a laser with self-phasing of the modes (for example, at $\lambda = 1.06$ μ) [3,4]. Promising media for two-quantum amplification are organic dyes, which have strong absorption in the region $\lambda = 0.3$ - 0.4 μ (pumping by the second harmonic of a ruby laser is possible) and a wide band of prolonged fluorescence in the $\lambda = 0.53$ μ region. If one succeeds in finding a dye with two-quantum gain $\alpha_{0m} \approx 10^{-2}$ cm^{-1} in a field of energy density 50 MW/cm^2, then it is advantageous to place this dye inside a laser with mode self-phasing by a nonlinear absorber as the second nonlinear element, which goes into operation after the action of the saturating absorber ceases. Such a laser will apparently be able to emit light pulses with duration up to 10^{-13} sec and energy up to 0.1 - 1 J/cm^2.

4. An advantage of this method of amplification as compared with the generation

method for obtaining two-quantum negative absorption is connected with the possibility of working with radiation pulses having an intensity lower by two or three orders of magnitude than in the case of generation. This is due to the relatively long pulse time ($>10^{-9}$ sec) in the case of generation, owing to the finite dimensions of the resonator. In the amplification method it is possible to operate with pulses shorter by several orders of magnitude.

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TURBULENT HEATING OF A PLASMA BY ELECTROMAGNETIC WAVES

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It was observed in a number of experiments on plasma heating by high-frequency electromagnetic waves [1,2] that the rate of absorption of the energy of the hf field is anomalously large compared with the value calculated with only pair collisions taken into account. Thus, in experiments of plasma heating by a magnetosonic wave [1] it was established that the protons are heated to a temperature 100 eV. The main parameters of the experiments were: generator frequency $f = 2 \times 10^7$ sec^{-1}, constant magnetic field intensity $H_0 = 2 \times 10^3$ Oe, alternating field intensity $H_\sim < 60$ Oe, charged-particle concentration $n \sim 10^{13}$ cm^{-3}, electron temperature $T_e \leq 10$ eV, transverse dimension of plasma pinch $r_0 = 3$ cm, and magnetosonic wave damping decrement 2×10^7 sec^{-1} [sic!].

We shall show theoretically in this note that under the conditions of the experiments of [1] the electric current flowing through the plasma can be the cause of the instability. We present an equation for the heating of the plasma ions, determine the limiting values of the ion temperature and the wave decrement in the plasma, and compare them with the experimental results of [1].

1. The electromagnetic wave produces a current in the plasma. We are interested in the instability of a current-carrying plasma under conditions when the ion temperature exceeds the electron temperature. This problem was analyzed in [3,4]. The instability can be determined from the following dispersion equation: