Generation of short laser pulses during coherent amplification

A. V. Nazarkin, I. A. Poluéktov, and I. I. Sobel'man
P. N. Lebedev Physics Institute, Academy of Sciences of the USSR, Moscow

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Laser pulses can be frequency-converted by an $n\pi$-pulse technique with a high energy efficiency and with a substantial reduction in length.

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In this letter we show that when an $n\pi$ pulse passes through a resonant-absorption medium it may efficiently transfer energy to a pulse at the frequency of an adjacent transition, and the length of the new pulse may be substantially smaller than that of the original $n\pi$ pulse. For definiteness, we consider a medium of three-level atoms (Fig. 1) in which a stationary 2π pulse with a frequency $\omega_0 \approx \omega_{31}$ and a length τ_0 is propagating. The group velocity of the pulse, v_0, is much smaller than the phase velocity of light in the medium, c since most of the energy of the pulse goes into exciting the medium to level 3 (Ref. 1). We assume that propagating immediately behind this 2π pulse in the medium is a weak signal pulse with a frequency $\omega_s \approx \omega_{32}$ and length $\tau_s < \tau_0$. We have $v_s \approx c$ and thus $v_s \gg v_0$. Since level 2 is not populated, and since $\tau_s < \tau_0 \ll T_1, T_2$, the part of the medium covered by the 2π pump pulse is a coherently amplifying medium for the signal pulse which is propagating through it.

We describe the light pulses propagating along the z axis by

$$e_0(z,t) = \frac{1}{2}\left(E_0(z,t)\, e^{i(\omega_0 t - k_0 z)} + \text{c.c.}\right),$$

$$e_s(z,t) = \frac{1}{2}\left(E_s(z,t)\, e^{i(\omega_s t - k_s z)} + \text{c.c.}\right),$$

where E_0 and E_s are "slow" complex amplitudes, and k_0 and k_s are the wave vectors of the corresponding fields. The system of self-consistent equations for the fields and

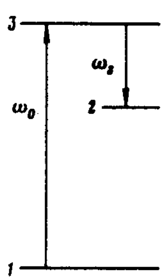

FIG. 1.

the medium is

$$\frac{\partial E_0}{\partial z} + \frac{1}{c}\frac{\partial E_0}{\partial t} = i\frac{2\pi\omega_0 N}{c}\mu_{13} < \sigma_{13} > ,$$
(1)
$$\frac{\partial E_s}{\partial z} + \frac{1}{c}\frac{\partial E_s}{\partial t} = i\frac{2\pi\,\omega_s N}{c}\mu_{23} < \sigma_{23} > ,$$

$$\frac{d\sigma_{13}}{dt} + i\Delta_0\sigma_{13} = -\frac{i}{2\hbar}[\mu_{13}(\sigma_{33} - \sigma_{11})E_0 + \mu_{23}E_s\sigma_{12}],$$
(2)
$$\frac{d\sigma_{23}}{dt} + i\Delta_s\sigma_{23} = -\frac{i}{2\hbar}[\mu_{23}(\sigma_{33} - \sigma_{22})E_s - \mu_{13}\sigma_{12}^* E_0],$$

$$\frac{d\sigma_{12}}{dt} + i(\Delta_0 - \Delta_s)\sigma_{12} = -\frac{i}{2\hbar}[\mu_{13}\sigma_{23}^* E_0 - \mu_{23}\sigma_{13}E_s^*],$$

$$\frac{d\sigma_{11}}{dt} = -\frac{i}{2\hbar}\mu_{13}\sigma_{13}^* E_0 + \text{c.c.}; \qquad \frac{d\sigma_{22}}{dt} = -\frac{i}{2\hbar}\mu_{23}\sigma_{23}^* E_s + \text{c.c.},$$

$$\sigma_{11} + \sigma_{22} + \sigma_{33} = 1.$$

Here $\Delta_0 = \omega_0 - \omega_{31}$; $\Delta_s = \omega_s - \omega_{32}$; μ_{13} and μ_{23} are the transition dipole moments; σ_{ij} are the elements of the density matrix of the three-level system; and N is the number density of particles in the medium. The angle brackets denote an average of σ_{ij} over the inhomogeneous width of the transition line.

For some simple analytic estimates we will initially restrict the discussion to the case of homogeneous broadening and $\Delta_0 = \Delta_s = 0$. We adopt the initial E_s profile

$$E_s(\xi) = E_{s0}\exp(\xi/\tau_{s0}) \qquad \xi < 0,$$
(3)
$$E_s(\xi) = 0 \qquad \xi > 0,$$

where $\xi = t - (z/c)$. We assume that the energy transfer to the pulse E_s is slight, so that we may ignore the deformation of the E_0 pulse. We assume that E_0 is a stationary 2π pulse; then[1]

$$E_0(z,t) = \frac{2\hbar}{\mu_{13}\tau_0}\,\text{ch}^{-1}\left(\frac{t - \frac{z}{v_0}}{\tau_0}\right), \qquad v_0 \approx \frac{\hbar c}{\pi\omega_0\mu_{13}^2 N\tau_0^2} \quad (4)$$

The population of level 3 is

$$\sigma_{33} = \mathrm{ch}^{-2}\left(\frac{t - \dfrac{z}{v_0}}{\tau_0}\right) . \tag{5}$$

Substituting (5) into (2), and setting $\sigma_{22} = \sigma_{12} = 0$, we find from (1), in the region $\xi < 0$,

$$E_s(z, \xi) = E_s(\xi)\exp(\beta\lambda(z)), \tag{6}$$

$$\beta = \frac{\pi N \mu_{23}^2 \omega_s \tau_{s0}}{\hbar c}, \qquad \lambda(z) = \tau_0 v_0\left(\mathrm{th}\frac{z}{\tau_0 v_0} + 1\right) . \tag{7}$$

After the pulse E_s passes through E_0 ($z \to \infty$, $\lambda \to 2\tau_0 v_0$), its total amplification is determined by the factor

$$f = \exp\left[2\frac{\tau_{s0}}{\tau_0}\frac{\omega_s}{\omega_0}\left(\frac{\mu_{23}}{\mu_{13}}\right)^2\right] . \tag{8}$$

For an important amplification of the pulse E_s we need $(\omega_s/\omega_0)(\mu_{23}/\mu_{13})^2 > \tau_0/\tau_{s0}$. With the appropriate choice of the transitions $1 \to 3$ and $3 \to 2$ ($\mu_{23}/\mu_{13} \gg 1$), we thus have a real opportunity for transferring energy from the pulse E_0 to the significantly shorter pulse E_s.

In addition, there is the possibility of a situation in which the quantity

$$\theta_s = \frac{\mu_{23}}{\hbar}\int_{-\infty}^{\infty} |E_s| dt \tag{9}$$

can reach a value of π. Such a π pulse is known[1,2] to be stable in a coherently amplifying medium. It completely removes the population inversion and is itself both amplified and shortened. According to (6)–(8), the condition for the generation of the π pulse is

$$\frac{\mu_{23}}{\hbar}\tau_{s0}E_{s0}\exp\left[2\frac{\tau_{s0}}{\tau_0}\frac{\omega_s}{\omega_0}\left(\frac{\mu_{23}}{\mu_{13}}\right)^2\right] \geqslant \pi . \tag{10}$$

The extreme value of τ_s corresponding to the quantum pumping efficiency $\eta \sim 1$ is

$$\frac{\tau_s}{\tau_0} \approx \frac{\omega_0}{\omega_s}\left(\frac{\mu_{13}}{\mu_{23}}\right)^2 . \tag{11}$$

Although Eqs. (6)–(8) are generally inapplicable to the case $\eta \sim 1$, a numerical solution of system (1), (2), shows that relations (10) and (11) can be used for estimates even in this case.

We turn now to the results of numerical calculations. In these calculations the quantity (μ_{23}/μ_{13}) is varied over a broad range, from 1 to 25. In all cases the initial value $\theta_s(z = 0)$ is assumed to be much smaller than π. The inhomogeneous broadening, $\Delta\omega_D = (1/T_2^*)$, is taken into account. The results depend strongly on the value of θ_s reached in the course of the process.

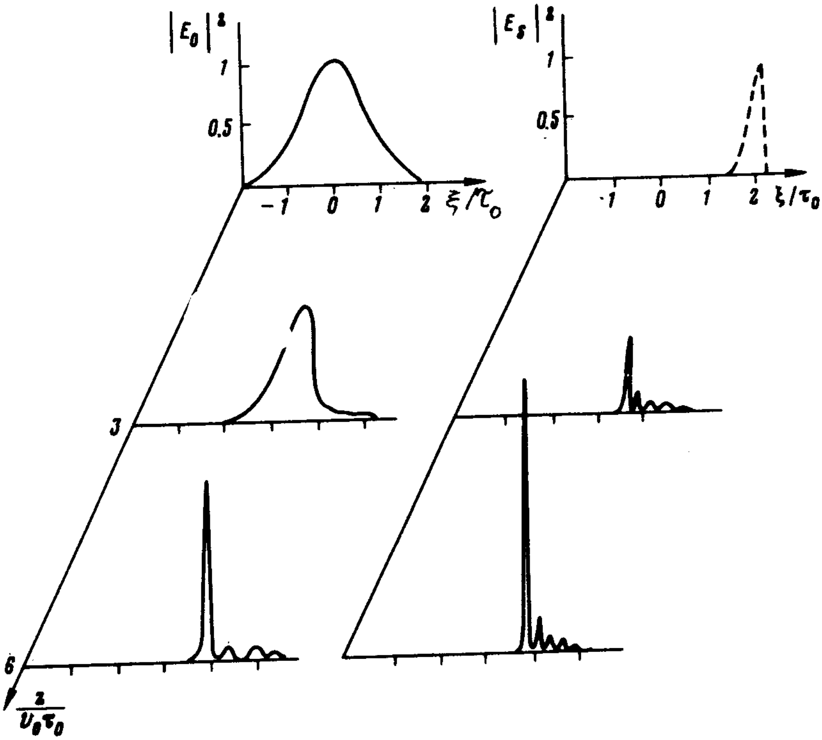

FIG. 2. Evolution of the 2π pump pulse $|E_0|^2$ and of the signal pulse $|E_s|^2$. The initial $|E_s|^2$ pulse is magnified by a factor of 10^7.

1. Specifically, if $\theta_s \ll 1$, the energy transfer to the pulse E_s is slight.

2. If $\theta_s \sim 1$ but $\theta_s < \pi$, a significant fraction of the energy of the initial 2π pulse is transferred. The length of the pulse E_s remains roughly constant at $\tau_s \sim \tau_{s0}$.

3. If θ_s reaches a value of π rapidly, there is an essentially complete transfer of energy ($\eta \sim 1$), accompanied by simultaneous compression of the E_s pulse to a length τ_s of the same order of magnitude as in (11). Figure 2 illustrates the situation with the results of a specific calculation for sodium vapor. Levels 1, 2, and 3 are chosen to be the 3s, 4s, and 4p levels, respectively; here $\lambda_{31} = 0.3303$ μm, $\lambda_{32} = 2.2084$ μm, $\mu_{13} = 10^{-18}$ esu, $\mu_{23}/\mu_{13} = 25$, $\tau_0 = 5\times10^{-10}$ s, and $\tau_{s0} = 10^{-10}$ s. Inhomogeneous broadening with $T_2^* = 1.5\times10^{-10}$ s is taken into account. The pump wavelength λ_0 and the signal wavelength λ_s are assumed to be $\lambda_0 = \lambda_{31}$ and $\lambda_s = 2.2083$ μm. The conditions for a 2π pulse correspond to $I_0 \approx 10^6$ W/cm^2; the signal intensity at the entrance is assumed to be $I_s = 0.1$ W/cm^2. The values selected for λ_0, I_0, λ_s, and I_s correspond to existing lasers: a flashlamp-pumped dye laser[3] and (one of the output lines of) an argon laser.[3]

It follows from these calculated results that in this case θ_s rapidly reaches values of π, so that the signal pulse is rapidly amplified and compressed. Its output intensity is $I_s \gtrsim 10^6$ W/cm^2; the quantum conversion efficiency is $\eta \approx 0.8$; and the pulse length is $\tau_s \sim 10^{-12}$ s.

Effective energy transfer from the pulse E_0 to the pulse E_s also occurs in the general case of n 2π pump pulses.

We note in conclusion that the pump pulse could be pulses with a frequency ω_0, which corresponds to a two-photon resonance with the transition $1 \to 3/(\omega_{31} \approx 2\omega_0)$ (Ref. 1).

[1]I. A. Poluéktov, Yu. M. Popov, and V. S. Roitberg, Usp. Fiz. Nauk **114**, 103 (1974).
[2]P. G. Kryukov and V. S. Letokhov, Usp. Fiz. Nauk **99**, 169 (1969).
[3]Spravochnik po lazeram (Laser Handbook), Sov. Radio, Moscow, 1978.

Translated by Dave Parsons
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