PROPAGATION VELOCITY OF A POWERFUL LIGHT PULSE IN AN INVERSELY POPULATED MEDIUM\

PHYSICS

1965

SovietRxiv

Abstract

Full Text

UDC 621.375.9

PHYSICS

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PROPAGATION VELOCITY OF A POWERFUL LIGHT PULSE IN AN INVERSELY POPULATED MEDIUM*

1. The propagation of a powerful light pulse in a medium with inverse population of two levels is considered. When the energy density of the light pulse is of the order of $E_s = \hbar\omega_0/2\sigma_0$ (ω_0 and σ_0 are the frequency and cross section of the radiative transition between the levels), sufficient for a considerable decrease in the initial inversion density N_0, an essentially nonlinear amplification of the pulse begins (^{1}). On the basis of the rate equations for radiation transfer it can be shown that, as soon as the energy density in the leading part of the pulse reaches the value E_s, all the active particles emit on the leading front, while the trailing front propagates in the medium with considerably smaller amplification or even with losses. As a result, the pulse maximum undergoes an additional displacement forward. After passage through a distance $\sim 1/\gamma$ (γ is the coefficient of light losses per unit length in the medium), the pulse energy reaches a stationary value (^{2}), and upon further motion the pulse tends toward a stationary form, moving with an effective velocity v_{eff} exceeding the velocity of light in the medium c.

A powerful Q-switched light pulse with instantaneous switching-on of the Q-factor always has an exponential leading front $\sim e^{t/\tau_0}$ (^{3}), and the pulse duration is always considerably greater than the transverse relaxation time T_2 of the medium (ruby: $T_2 = 10^{-11} \div 10^{-12}$ sec). It can be shown that, in the propagation in a medium with inverse population of such a pulse, the duration of the leading part of the pulse τ_f (from half-maximum to maximum) practically does not change. Such a pulse reaches a stationary state with duration ($\sigma_0 N_0 \gg \gamma$):

$$\tau_{\text{imp}} = \tau_f \left(\frac{\sigma_0 N_0}{\gamma}\right) \Big/ \ln\left(\frac{\sigma_0 N_0}{\gamma}\right), \qquad (1)$$

the propagation velocity of which is determined by the relation

$$\frac{v_{\text{eff}}}{c} = 1 + (\sigma_0 N_0 - \gamma)\tau_0 c. \qquad (2)$$

Fig. 1

Figure 1: Fig. 1

For typical parameters of a ruby medium ($\sigma_0 N_0 \simeq 0.2$ cm^{-1}, $\gamma \simeq 0.03$ cm^{-1}, $c = 1.7 \cdot 10^{10}$ cm/sec, and $\tau_0 = 3 \cdot 10^{-9}$ sec) we obtain $v_{\text{eff}} = 17 \cdot 10^{10}$ cm/sec. The displacement of the pulse maximum takes place with a velocity much greater than the velocity of light. This, of course, does not contradict the principle of causality, since such displacement is realized through deformation of the initially weak leading front of nonzero intensity. If a part of the leading front of the pulse is cut off, then the pulse moves only up to the point of zero intensity, which always moves with the velocity of light in the medium c.

2. The propagation of a powerful light pulse was studied experimentally with the aid of an amplifier consisting of two ruby crystals ···24 cm long, with end faces cut at the Brewster angle. The light pulse was obtained with the aid of the generator described in (^{4}). The total gain of the optical amplifier for a weak signal was about 50. According to estimates, the energy density in the front part of the pulse reached the value $E_s \simeq 4$ J/cm^2 at a distance of the order of 10–15 cm from the output end of the amplifier. The pulse energy at the amplifier output reached 17 J.

Recording of the light pulses before and after the amplifier was carried out with the aid of one and the same coaxial photocell; moreover, the amplified pulse traveled an additional path of several tens of meters and reached the photocell $56 \cdot 10^{-9}$ sec after the arrival of the input pulse. The pulses were attenuated accordingly in order to ensure a linear operating regime of the photocell. Figure 1a shows a typical oscillogram of the input and output pulses for a weak signal. (The generator pulse was attenuated by a factor of $3 \cdot 10^3$ with filters.) The parameters of the unattenuated input pulse were: energy 1.3 J, duration at half-height $16 \cdot 10^{-9}$ sec; the beginning of the pulse, determined by the moment of switching on the shutter in the generator, is $45 \cdot 10^{-9}$ sec from the peak of the pulse; the duration of the leading edge (from the 1/2 level to the maximum) is $8 \cdot 10^{-9}$ sec.

Fig. 1

Figure 1b (in Fig. 1c a sinusoid with period $8 \cdot 10^{-9}$ sec is shown for sweep calibration) gives the oscillogram of the input and output pulses for an unattenuated signal. From comparison of the oscillograms in Figs. 1a and 1b it may be noted that no substantial shortening of the pulse occurs; instead, the output pulse in Fig. 1b is at a closer distance with respect to the input pulse than in

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* A detailed exposition of this question and of the effects associated with it will be published separately.

Fig. 1a (the light delay in the experiments was not changed). Processing of the oscillograms gives for this shift the value $9 \cdot 10^{-9}$ sec.

In accordance with the concepts developed above, it must be assumed that, as the peak of the pulse passed through the amplifier in the nonlinear regime, it moved with a velocity exceeding the velocity of light in vacuum by a factor of 6-9. In the experiment $\sigma_0 N_0 = 0.14$ cm^{-1}, $\gamma \simeq 0.02$ cm^{-1}, $\tau_0 = 4 \cdot 10^{-9}$ sec, and the distance of substantially nonlinear amplification was $L \simeq 10$—15 cm. In this case, according to (2), $(v_{\text{eff}} - c)/c \simeq 8$. In passing through a section of the medium L, the pulse is additionally displaced by $(v_{\text{eff}} - c)L/c$ cm, which leads to an advance of

$$\frac{(v_{\text{eff}} - c)}{c} \frac{L}{c} = 5 \div 7 \cdot 10^{-9} \text{ sec.}$$

Since the mechanism of displacement of the pulse maximum begins to operate somewhat earlier than the energy in the front part reaches 4 J/cm^2, the experimental advance should exceed this estimate. The experimentally obtained value of $9 \cdot 10^{-9}$ sec does not contradict the concepts developed above.

3. Thus, preferential amplification of the front part of a pulse with an exponentially rising leading edge leads not to a shortening of the pulse duration, but to an additional displacement of the pulse maximum. For a substantial shortening of the pulse duration it is necessary to increase the steepness of the leading edge, for example by cutting off

of the front part by an additional shutter, nonlinear absorption, etc. The possibilities of these methods will be published separately.

It should be noted that the displacement of the pulse maximum with an effective velocity $v_{\text{eff}} > c$ is accompanied by displacement of the boundary of the inversion population, since the pulse maximum propagates in a medium with inversion $\ll N_0$. It is clear that the pulse is accompanied by a gradient $\operatorname{Im} \varepsilon$ moving with velocity v_{eff}, by a clump of the volume-averaged polarization of the medium, and by a clump of the high-frequency polarization of the medium, which may lead to the appearance of a number of new effects, for example Vavilov-Cherenkov-type radiation.

The authors consider it their pleasant duty to express their deep gratitude to M. P. Vanyukov and L. D. Khazov for assistance in carrying out the present experiment.

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Received
31 VII 1965

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