Suppression of phase relaxation in semiconductors; coherent emission of the active medium of a picosecond injection laser

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The envelope of a picosecond pulse emitted by a Q-switched injection laser operating in the strong-field regime has been observed to split into subpulses. The effect is explained on the basis of a suppression of intraband relaxation in the GaAs by the strong field of the pulse and on the basis of a manifestation of a coherent interaction of the electromagnetic field with the semiconductor.

1. To the best of our knowledge, the emission of light in a regime of coherent emission of a medium has not yet been achieved. [In its pure form, this would be a coherent emission by an ensemble of particles with infinite longitudinal and transverse relaxation times T_1 and T_2, respectively. The polarization vector P of the particles varies in accordance with $P \sim \sin(\mu/\hbar)\int E dt$, where μ and E are the dipole moment and field amplitude of the light.] The explanation lies in the serious difficulties in simultaneously satisfying the conditions for a pulsed emission of particles and the requirement that the pulse length τ be small in comparison with T_2. In semiconductors, for example, T_2 is $\sim 10^{-13}$ s at 300 K. The formation of T_2 in a semiconductor is governed by several factors (electron-phonon coupling, electron-electron coupling, etc.), each of which is characterized by a corresponding time τ_c, which causes a line broadening.

We know from the theory of the relaxation of quantum systems in a resonant electromagnetic field that in each elementary relaxation-collision event photons of the field also participate. The extent of their participation is determined by the relation between the times τ_c and $\Omega^{-1} = (\mu E/\hbar)^{-1}$—the Rabi period. In a strong field, with $\Omega > \tau_c^{-1}$, the corresponding relaxation mechanism is suppressed. The time T_2 thus becomes a function of[1)] E, specifically, an increasing function. If the condition for the coherence of the interaction of the field with the particles, $\tau \ll T_2(E)$, does not hold in weak fields, it may hold in strong fields.

2. Experiments were carried out with an injection laser (GaAs/AlGaAs, $\lambda = 850$ nm) in modified Q-switched operation.[4] The distinctive features of the dynamics of the laser population inversion in this method, which stem from the electric field additionally introduced in the laser, make it possible to build up an inversion of a factor of $\eta = 7$–10 in the amplifying regions of the laser before the Q switching. This inversion exceeds the threshold value in the case of a bleached absorber ($\eta = 1$). The values found experimentally are $\tau = 5 \pm 2$ ps, $\Omega = 10^{13}$ rad/s (with $\mu = 2\times 10^{-17}$ esu for GaAs), and a power flux density no less than 4×10^8 W/cm^2 at the laser output. Consequently, and in contrast with other picosecond injection lasers, in this laser we are dealing with a strong field, $\Omega\tau_c \gtrsim 1$, with a fairly low value of τ. We can thus expect to see manifestations of a coherence of the interaction of the pulses with the active medium of the laser, despite the relation $T_2(0) \ll \tau$.

Figure 1 shows the experimental results on the shape of the envelope of the

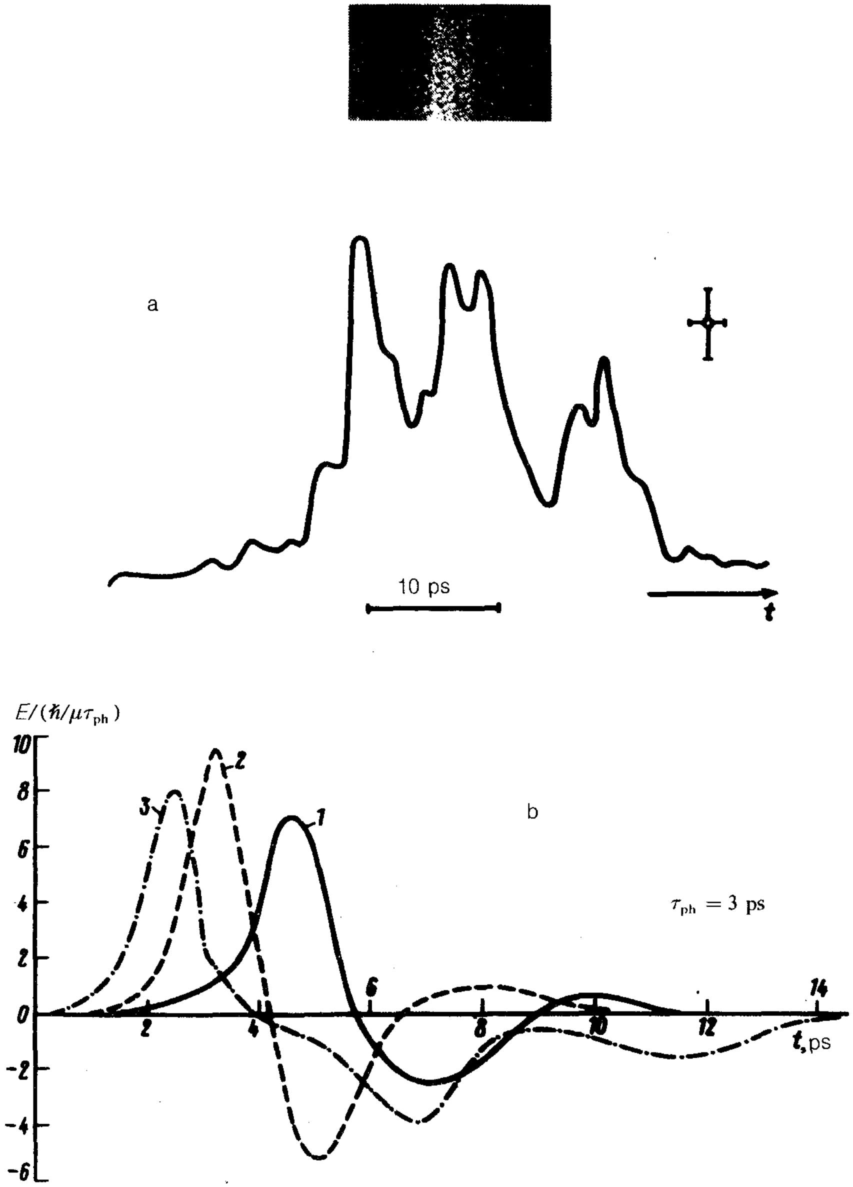

FIG. 1. a—Experimental shape of the envelope of picosecond pulses in the laser with $\eta \approx 8$–10; b—calculated envelopes of pulses in the case of a homogeneous linewidth and (1) $\eta = 6$ or (2) $\eta = 9$ and an inhomogeneous linewidth ($T_2^{\rm homo} = 1.5$ ps; $T_2^{\rm in} = 0.1$ ps) and $\eta = 16$.

picosecond pulse. This shape demonstrates a breakup of the single pulse into three subpulses (see Ref. 4 for a detailed description of the measurements of the lengths). The laser generates pulses with a smooth, Gaussoid envelope in essentially all cases. A breakup into subpulses (two, three, etc.; up to four were found experimentally) is observed only when it is possible to achieve the maximum value of η (the extent to which the initial population inversion exceeds the threshold), which is about 8–10. The appearance of several pulses, instead of one, is not a consequence of multiple reflections of the same pulse from the facets of the laser diode, since the distance between them changes with a change in the laser pumping level, while the time required for a back-and-forth traversal of the laser resonator by the light is fixed: 15 ± 1 ps for a laser 490 μm long. Unfortunately, at the moment we have essentially no reliable experimental methods for determining the change in the sign of the envelope of the field of picosecond pulses. Accordingly, we do not know whether the sign of the field envelope changes in Fig. 1a. The detection of a change in sign would be the most convincing proof for a coherence of the interaction of the field with the medium. Since the pulse lengths, the separation between pulses, and the time resolution (2 ps) of the Agat image-converter camera used in the present experiments are all comparable, and because of the particular method used to produce an image of the optical process under study in this camera, the pulses in Fig. 1a may not be completely resolved.

3. A theoretical analysis of the operation of a Q-switched laser with the parameters of the injection laser used shows the following: If we take T_2 to be independent of E, equal to $T_2(0) \approx 10^{-13}$ s, i.e., much shorter than $\tau_{\rm ph}$ [the photon lifetime in the laser resonator ($\approx$3–4 ps)], then the output from the laser would be a single pulse over a time scale of 3×10^{-11} s. From the known solutions of the laser rate equations we then find a bell-shaped field envelope with a length[5] of $(2–3)\tau_{\rm ph}$. If, on the other hand, we assume that T_2 is a monotonically increasing function of E with $T_2(0) = 10^{-13}$ s, we conclude that the field amplitude is an oscillating function of the time.

Figure 1b shows calculated shapes of the envelopes of picosecond pulses for a Q-switched laser and for the injection-laser parameters $\tau_{\rm ph} = 3$ ps, $T_2(0) = 10^{-13}$ s, and $T_2(\infty) = 2\ {\rm ps} < \tau_{\rm ph}$, for various values of η (equations corresponding to those of Ref. 6 were solved). For all of the injection lasers except that described in Ref. 4 and that which we used, η is just barely larger than 1. A calculation shows, and the experiments confirm, that at $\eta \lesssim 2–4$ the pulses have a smooth shape in this case (line 1 in Fig. 1b), while at large values of η oscillations appear in the field envelope. The duration of each subpulse in this coherent generation regime is $(0.8–1.2)\tau_{\rm ph}$. Incorporating the inhomogeneity of the line (an important point in semiconductor lasers for times < 1 ps) does not change the shape of the envelope in any qualitative way; it simply causes a slight increase in the separation of the oscillations in the field envelope. A detailed theoretical analysis of the coherent operating regime of a semiconductor laser will be published in the future.

4. In summary, we believe that in this Q-switched injection we have experimentally achieved the second case: the case of the coherent emission of picosecond pulses by the active medium of the laser. The observation of a breakup of the envelope of the pulses into subpulses at large values of η is unambiguous evidence for a coherent interaction of the field with the active mediun of the laser. The relation $T_2(0) \ll \tau \approx \tau_{\mathrm{ph}}$ implies that this result is evidence of a suppression of the phase relaxation within the bands in the semiconductor by the strong field ($\Omega > \tau_c^{-1}$). Since we have $\tau \cong \tau_{\mathrm{ph}}$ and $\tau_{\mathrm{ph}} \sim L/c$, where L is the length of the laser, a decrease in L to 50–60 μm would make it possible to achieve pulses $\sim$100 fs long from injection lasers by this method. This opportunity is clearly of interest for research on femtosecond phenomena.

(1) The effect of a field on relaxation times was first studied in Ref. 1 in connection with a nuclear magnetic resonance. The effect has been predicted in the optics of gases[2] and in semiconductors.[3]

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