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Regenerative amplification of subnano- and picosecond pulses in rare-gas halide excimer amplifier

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Numerical investigations of noncoherent amplification of short pulses in a regenerative rare-gas halide excimer amplifier have been performed. The amplifier's model, in particular, includes the vibrational relaxation and collisional mixing of the B, C states of excimer molecule, amplified spontaneous emission and a possible presence of additional saturable absorber in the resonator. There was analysed the influence of the input pulse parameters on energy, power, duration, and contrast of the amplified pulse in a regenerative and two-pass system of parameters typical for the KrF amplifier. It was found that the regenerative amplifier and, first of all, amplifier with a properly matched absorber in the resonator, can ensure higher pulse parameters than the single- or two-pass amplifier, and it can be an attractive alternative for non-regenerative systems used in short-pulse high-power excimer lasers.

1. Introduction

One of essential but not fully resolved problems met in non-storage laser systems (of short life-time of the upper laser level) is how to achieve simultaneously high efficiency of energy extraction from the medium and high contrast ratio of the lower pulse. The solution of this problem is of special importance for the rare-gas halide excimer systems generating short- and ultrashort pulses of high power [1]–[6]. In the up-to-date works devoted to the problem of pulse amplification in such systems both in experimental examinations [3], [7]–[10] and in theoretical analyses [11]–[16] the attention was concentrated on the examinations of single- or two-pass amplifying systems. Although a doubtless advantage offered by such systems is their simplicity far as design and exploitation are concerned the energy extraction efficiency in such systems is usually small. Since this efficiency is roughly proportional to the quotient $\Delta t/T_p$ ($T_p \approx 10^{-8}-10^{-6}$ s – pumping time of the medium, Δt – time of the radiation–medium interaction) in large excimer laser systems (of power of TW order) the so-called method of optical multiplexing is applied [1], [5], [17]. In this method, a short pulse from the generating system is divided spatially into a large number of parts (beams) which after a suitable delay with respect to each other are directed to an amplifier in the form of a train of pulses of duration close to T_p. Thanks to this, during a significant part of the pumping process the medium is saturated by the amplified radiation. Such a solution requires, however, very complex and expensive optical systems and in smaller laser systems is difficult to accept for economical reasons. Another possible solution is to enable a multi-pass of the pulse through the amplifying medium in a regenerative system.

The advantages offered by the application of the regenerative amplifier in excimer systems are not obvious since, although the multi-pass of the pulse through the medium results in an increase of extraction efficiency, the regenerative system itself enables an intensive development of the amplified spontaneous emission leading generally to both degeneration of the medium gain and lowering of the pulse contrast ratio. A determination of such a solution requires some more detailed investigations to be carried out.

In this work, some examinations of amplification of subnano- and picosecond pulses in a regenerative rare-gas halide amplifier were performed by using computer simulation. The numerical calculations were carried out for system parameters typical for KrF excimer amplifier assuming noncoherent radiation—matter interaction. In this model, collisional mixing of B, C states of the excimer molecule and the vibrational relaxation in those states have been encountered. A regenerative amplifier both without absorber and with an absorber in the resonator has been analysed. The parameters of a pulse emerging from the regenerative amplifier have been compared with those of a pulse at the output of a two-pass amplifier.

2. Model of the amplifier

Schemes of a regenerative (a) and a two-pass (b) amplifier are shown in Fig. 1. The regerative amplifier contains a resonator composed of two totally reflecting mirrors, active medium, and an electrooptic switch. Additionally, a nonlinear saturable absorber may be located inside the resonator. The laser pulse is introduced to the resonator by a switchs being next, after a suitable number of passes through the resonator, led out by the same switch outside the resonator. In the calculations, it has been assumed that the switch is of two-direction type (for instance, composed of

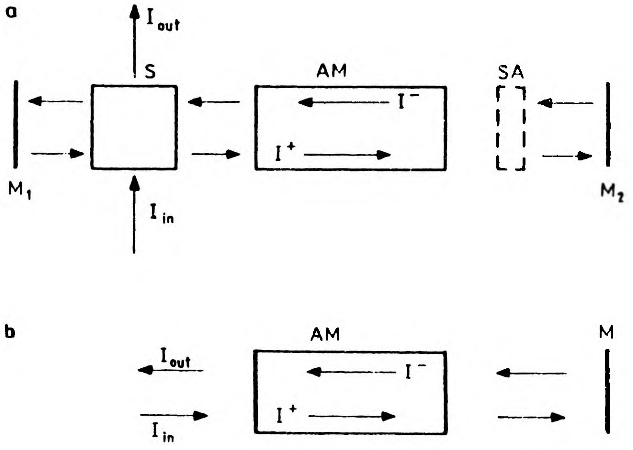

Fig. 1. Scheme of the regenerative (a) and two-pass (b) amplifier used in the calculations (AM — amplifying medium, SA — saturable absorber, S — switch, M, M_1, M_2 — mirrors)

a Pockels cell inserted between two crossed polarizers) being controlled with the help of a simple voltage run in the form of a half-wave gate (Fig. 2). In the absence of voltage on the switch the losses in the resonator exceed the gain which prevents the generation to be developed in the resonator despite the pumping of the active medium being switched on. The laser pulse is introduced to the resonator (for instance, by one of the polarizers) after applying the half-wave voltage on the switch just at the moment when the losses on the switch are minimal and the gain exceeds the total losses in the resonator. In the subsequent passes through the resonator, the pulse is being amplified up to the moment when the voltage gate is closed. The decay of the voltage on the switch causes both a break of the amplifying process and a lead-out of the amplified pulse outside the resonator.

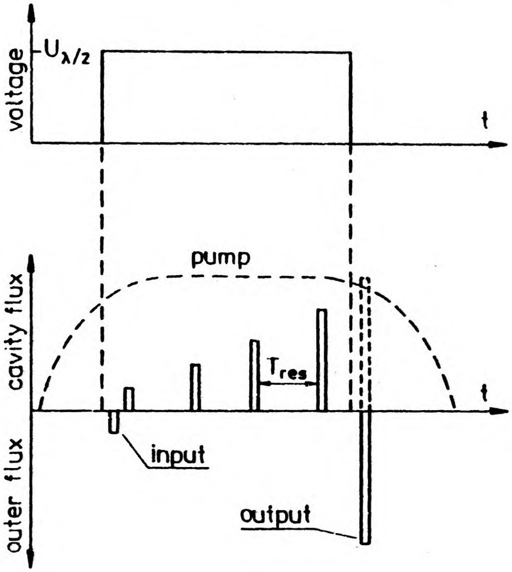

Fig. 2. Operation principle of the regenerative amplifier

The model of energy extraction from rare-gas halide laser presented in paper [18] being a modification of a four-state KrF laser model described in [11], has been accepted as a physical basis for computer analysis of the system presented above. The propagation of radiation in the system has been described by the following set of differential equations:

– Two transport equations for the photon flux (in positive $I^+$and negative I^- directions of the system axis) [19].

– Four population equations for N_B, N_C, N_L, N_K, where N_B, N_C – populations of B and C states in the excimer molecule, respectively, N_L – sum of populations of "laser" vibrational levels in the state B, N_K – sum of populations of respective vibrational levels in the state C [18].

– Equation for the absorption coefficient of the saturable absorber [20], in the case of the regenerative amplifier with an absorber.

The relaxation processes in the active medium are encountered in the equations by using six magnitudes: effective lifetimes τ_B, τ_C, τ_L, τ_K, the time of vibrational relaxation τ_V and the time τ_{BC} of collisional mixing of state B and C (for more detailed description, see [18]). The relaxation in the absorber is characterized by the time constant τ_a. It has been assumed that the pumping of the medium being quasi-stationary is described by the function $\exp[(-t/T_p)^4]$. The spontaneous emission is due to the term $\theta N_L/2\pi\tau_L^s$, where θ – radiation divergence, τ_L^s – time of spontaneous emission. Additionally, it has been assumed that the voltage U on the electrooptic switch increases and decreases exponentially with a characteristic time τ_s, while the transmission of the switch is described by the function $T(t) = T_0+(T_1-T_0)\times\sin^2[\pi U(t)/2U_{\lambda/2}]$, [19]. The numerical values of the parameters of the active medium being typical for a KrF laser have been accepted and, in particular: the cross-section for stimulated emission $\sigma = 2.4\times10^{-16}$ cm^2, the coefficient of linear losses $\rho =$ 0.01 cm^{-1}, $\tau_B = \tau_C = \tau_L = \tau_K = 1.5$ ns, $\tau_L^s = 8$ ns, $\tau_V = 0.5$ ns, $\tau_{BC} = 0.04$ ns, length of the active medium l = 40 cm. The pumping intensity of the medium has been established at the level corresponding to the small signal gain coefficient, at the maximum of the pumping pulse about 0.1 cm^{-1}. For the absorber, it has been assumed that $\sigma_a = 1.8\times10^{-16}$ cm^2, $\tau_a = 1.1$ or 0.1 ns, $\rho_a = 0.5$ cm^{-1}, $l_a = 0.6$ cm, while for the majority of the carried out calculations that: the absorption coefficient for small signal in the absorber $\gamma = 4.2$ cm^{-1} (this parameter was roughly optimized), resonator length $L_{res} = 60$ cm, $T_p = 50$ ns, $\tau_s = 0.5$ ns, $T_0 = 0.005$, $T_1 = 0.7$, $\theta = 1$ mrad. The shape of the pulse entering the amplifier has been assumed to be of the Gaussian function form. The system of differential equations has been solved numerically basing on the Runge–Kutta method. The numerical analysis has been limited to the pulses not shorter than 20 ps because of the low calculation speed of the available computer.

3. Results

The evolution of both the gain factor and the radiation intensity at the chosen point of the resonators of the regenerative amplifier without absorber (RA) and with an absorber (RASA) of long relaxation time τ_a = 1.1 ns are shown in Fig. 3. In the first case, an intensive development of the amplified spontaneous emission (ASE) in the amplifier resonator causes a quick increase of the background of the pulse, while the contrast ratio of the latter is decreased. This makes more difficult the effective regeneration of the gain in the medium between consecutive passes of the pulse through the latter which results in a rapid decrease of the pulse power, after having reached a maximum. In the case of an amplifier with an absorber, the development of ASE is essentially attenuated causing the contrast of the amplified pulse to be high and, moreover, the pulse power, after having exceeded the maximum, to change relatively slow. The presented image of pulse evolution in the amplifier is typical both for subnano- and picosecond pulses. Figure 4 shows the deformations in shape of the pulse (of maximum power) in the RA and RASA systems in the case of subnanosecond (500 ps) and picosecond (20 ps) pulses of the same input power. In the RA amplifier, the shortening of the pulse front slope is dominant (due to the gain saturation), the same being true for the elongation of

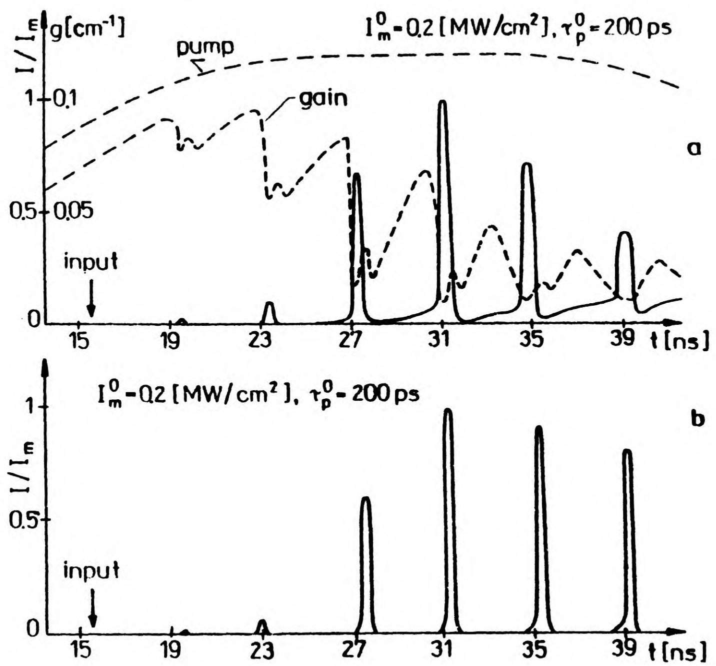

Fig. 3. Evolution of both the gain and the radiation intensity in the regenerative amplifier: a — RA, b — RASA

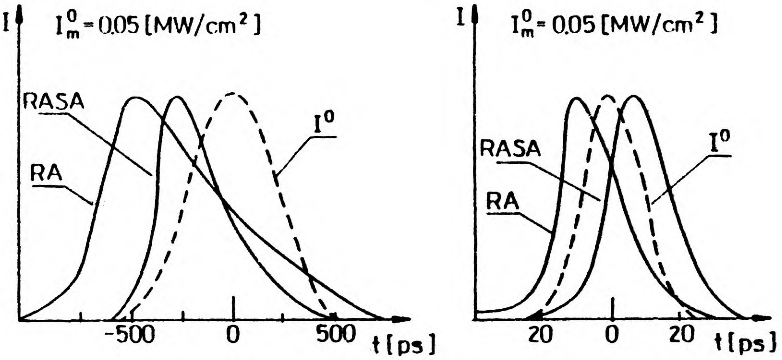

Fig. 4. Deformation of the pulse shape in the regenerative amplifier in the case of subnano- and picosecond pulses

the back pulse slope (due to vibrational relaxation and the mixing of the states B and C). This leads to an asymmetrization of the pulse, especially strong in the case of longer pulse (of higher energy). The absorber located in the system acts against the elongation of the pulse and under the suitable conditions may cause the shortening of the latter. The shown character of the deformation is typical for symmetric input pulses. In the case when the front slope of the input pulse is much shorter than the back slope an intensive gain saturation in the RA system may lead to formation of a sharp peak in the front part of the pulse duration many times shorter than the duration of the basic part of the pulse [21]. This effect may be balanced by a suitably chosen absorber causing an increased symmetrization of the pulse.

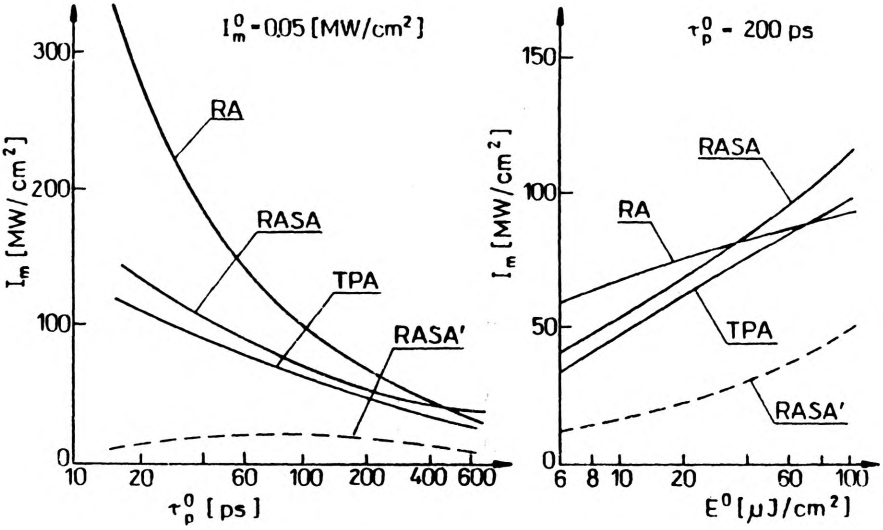

Fig. 5. Dependence of the peak power of the pulse emerging from the amplifier on the duration and the energy density of the input pulse for different types of amplifiers

The dependence of fundamental parameters of the pulse emerging from the amplifier* upon the duration and the energy density of the input pulse for three considered variants of the regenerative amplifier: RA, RASA, RASA' and the two-pass amplifier TPA are shown in Figs. 5–7 (RASA' denotes an amplifier with the absorber of shorter relaxation time $\tau_a = 0.1$ ns). The RASA' amplifier occurs to be less advantageous from the energetic point of view. The highest power and energy of the pulse for the low input energies may be obtained from an RA amplifier. In the region of high input energies, a higher pulse power is assured by the RASA system. The energetic parameters of the pulse from TPA system are close to those obtained from the RASA system. Due to high contrast ratio of the pulse a definite superiority of the RASA systems over the other ones may be noticed. Its advantages in relation to RA and TPA systems are especially visible in the region of high input energies. In all the systems considered, the contrast ratio increases with the increase of both energy and duration of the pulse. The changes in the pulse length in the RA, RASA and TPA systems are relatively small. A distinct pulse compression is observed in the RASA' system.

A regenerative rare-gas halide amplifier is a multiparameter system. The formulation of the unique relations valid for an arbitrary set of amplifier parameters

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* In the case of a regenerative amplifier, these parameters are attributed to the pulse emerging from the resonator at the moment of achieving its maximum amplitude (see Fig. 3).

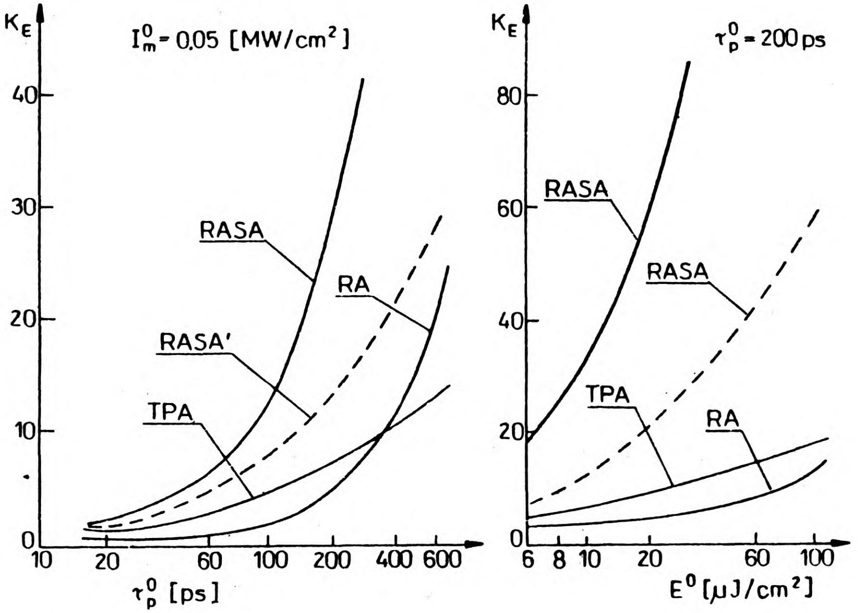

Fig. 6. Dependence of energetic contrast of the pulse emerging from the amplifier on the duration and energy density of the input pulse for different types of amplifiers

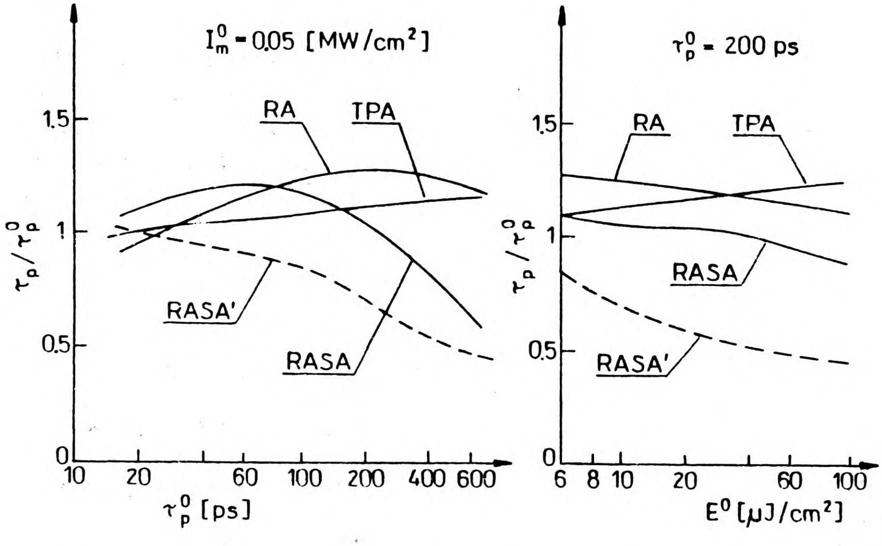

Fig. 7. Dependence of duration of the pulse emerging from the amplifier on the duration and energy density of the input pulse for different types of amplifiers

is difficult, due to a significant number and a possible alteration range of these parameters as well as the nonlinear character of the system. The above results are by no means of universal character and rather present an attempt to visualize some regularities occurring during regenerative amplification of short pulses in the excimer system as well as to show the possibilities of regenerative amplifier as compared with the conventional single- or two-pass ones.

4. Conclusions

The numerical examinations carried out allow us to formulate the following conclusions:

– Regenerative KrF amplifier offers a possibility of achieving higher power and shorter pulse duration than those offered by the single- or two-pass amplifiers commonly used.

– The contrast ratio of the pulse emerging from RA is small and, in general, lower than or close to the value of contrast ratio at the TPA output. Substantially higher contrast ratio may be obtained from RASA without or with low loss of power.

– RASA may be exploited as an "amplifier of power" or as a pulse "compressor". An absorber of relatively long relaxation time ($\tau_p^0 < \tau_a < T_{res}$), should be used in the first case, while the one of short relaxation time ($\tau_a < \tau_p^0$), in the other.

– The advantages of RASA are visible first of all in the case of input pulses of relatively high energy density ($E^0 \geqq 10^{-2}-10^{-1}$ mJ/cm^2).

– In order to achieve the parameters of the pulse from RASA higher than those from single- or two-pass amplifier a suitable choice of RASA parameters (coefficient of absorption, length of resonator, time interval of amplification, and the like) is necessary.

The above conclusions though formulated on the base of calculations carried out for the KrF amplifier are presumably valid also for other rare-gas halide amplifiers (XeCl, ArF, etc.), because of significant similarity of both laser level structures and relaxation processes occurring in those media. Therefore, the statement that the regenerative rare-gas halide amplifiers (in particular, RASA) may become an alternative for the nonregenerative systems used for generation of short high power pulses, seems to be justified.

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