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Numerical investigation of generation of ultrashort pulses in a XeCl excimer laser with electrooptical deflector

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Generation of ultrashort light pulses in a XeCl excimer laser by fast mode locking using an electrooptical deflector is investigated numerically. The influence of parameters characterizing the deflector as well as the gain, static losses, and pumping time of the laser on duration and power of the pulses generated is analysed in detail. We have found that in a XeCl laser, like in a KrF laser, using the method considered, it is possible to produce pulses of duration $<10^{-11}$ s at the laser pumping time not exceeding 50–100 ns.

1. Introduction

Ultrashort pico- and femtosecond light pulses find applications in numerous fields of studies, *e.g.*, spectroscopy and nonlinear optics, atomic and plasma physics, investigations of solid-state properties and molecular interactions in liquids, as well as photochemistry and biology (*e.g.*, [1]). The sources of ultrashort pulses (USPs) are, most frequently, dye lasers or solid-state lasers [1], [2] producing radiation in the visible or near-infrared region. To obtain USPs in these lasers, various kinds of the mode-locking are usually employed [1], [2].

Some of the above-mentioned applications require particularly USPs in the ultraviolet (UV) spectral region. The most effective sources of UV radiation are excimer lasers based on rare-gas halides (KrF, XeCl, ArF, *etc.*). Most of these lasers have broad gain bandwidth, which makes it possible to obtain pulses of pico- and femtosecond duration. However, their other properties – mainly short time of effective excitation of the medium (the occurrence of the gain in the medium) – cause that USP generation methods applied successfully in other lasers are little efficient with reference to excimer lasers. Conventional mode-locking methods (*e.g.*, with an acousto-optic modulator) employed in these lasers result in pulses of duration τ lying in the subnanosecond region, even at relatively long excitation times (100–300 ns) [3], [4]. Also, application of the methods employing nonlinear optical effects [5]–[8] has not brought about results auguring production of pulses shorter than 10^{-11} s directly in a laser oscillator.

In the works [9]–[11], the authors investigated the possibility of generation of USPs in a KrF excimer laser by fast periodic Q-switching using a Pockels cell (PC).

It was proved that, at the laser pumping times of $\sim 50-100$ ns in the active version of this method [9], [10], it was possible to obtain pulses of duration of some tens of picoseconds, whereas in the active-passive version (with a saturable absorber) [11], pulses of $\tau \leqslant 10^{-11}$ s could be obtained. The way of USP production described in [9]–[11] is a special case of a more general method which can be called fast mode locking (FML) [12]. In the FML method, an USP is formed by a train of short high-contrast-ratio transmission windows produced in the cavity by a fast modulator. If the duration τ_m of the transmission window was sufficiently short ($\tau_m \ll T_c$, where T_c is the cavity round-trip time), an USP would be able to be formed totally after merely several cavity round-trips [12]. Thus, in contradistinction to conventional mode locking (slow mode locking), where formation of an USP occurs during microseconds or longer times (the necessary number of cavity round-trips is large), the process of USP formation in the FML method can last merely some tens of nanoseconds. Hence, FML can be an efficient way for production of USPs also in short-gain-duration lasers such as excimer lasers.

The main limitation of the FML method accomplished with a PC modulator is the subnanosecond or longer voltage switching time τ_s on the PC and, thereby, a relatively long duration of the transmission window ($\tau_m \sim \tau_s > 10^{-10}$ s). Moreover, at practical cavity lengths ($L_c \sim 1$ m), the achievement of $\tau_m \leqslant 10^{-9}$ s requires application of a square wave of voltage driving the PC, the production of which is more difficult than that of a sine wave. In high-gain lasers, an additional limitation is also a relatively low contrast ratio ($\sim 10^2$) of the PC modulator. The above drawbacks appear to a considerably less degree in the case of a modulator using an electrooptic deflector (EOD). The application of an EOD makes it possible to obtain many times shorter transmission windows of the modulator [12]–[14] than by means of a PC and, moreover, allows the modulation depth to be considerably increased [15], [16]. Thus, the basic requirements for the accomplishment of FML can be fulfilled almost ideally in this case.

The features of USP generation by FML using an EOD for the case of a KrF excimer laser were investigated in [12]. It was proved that, at the laser pumping times even as short as $50-100$ ns, it was possible to produce pulses of duration in the $1-10$ ps range in that laser. On the basis of the results of that work, one can suppose that the method proposed there will be an efficient way for production of USPs also in other short-gain-duration lasers. The process of USP formation is nonlinear, however, and thus the course of this process and resulting duration of a pulse generated depend in general on the kind of the laser's active medium (its macroscopic and molecular parameters). For this reason, quantitative assessment of the effectiveness of the method and the influence of the laser parameters on characteristics of the pulses generated should be performed individually for each type of the laser.

This paper is a continuation of an earlier work [12] and is devoted to numerical investigations of the features of generation of USPs by FML using an EOD in a XeCl excimer laser. The influence of parameters characterizing operation of an EOD as well as the gain and static losses of the system on duration and power of a pulse are investigated for the case of the EOD driven with a sine wave and the EOD driven with a square wave of voltage.

2. Principle of the laser operation

The schematic diagram and the principle of operation of the laser with FML using an EOD are presented in Fig. 1 [12]. The laser cavity, limited by the M_1 and M_2 mirrors, contains an active medium, AM, and a loss modulator composed of an EOD and a diaphragm. The EOD is driven with a voltage wave of the amplitude V_0 and the period $T_m = nT_c$, where $n = 2, 1, 1/2, \ldots$. When the voltage V on the EOD differs from 0, the light beam passing through the EOD is deflected from the

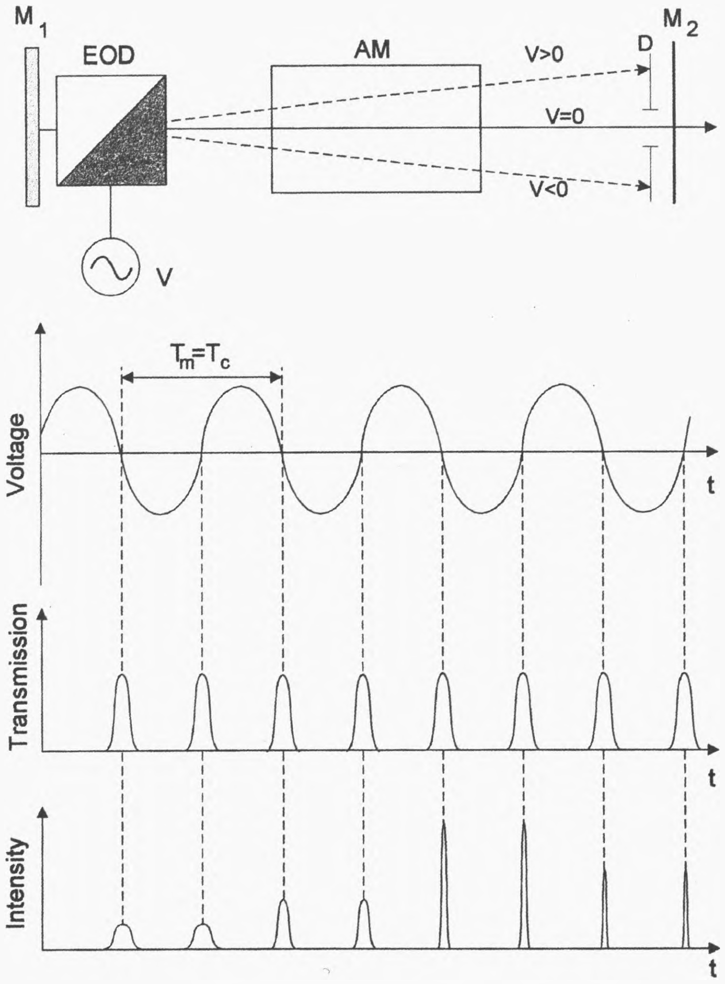

Fig. 1. Schematic diagram and principle of operation of short-pulse laser with fast mode locking using electrooptical deflector [12]. AM – active medium, EOD – electrooptical deflector, D – diaphragm, M_1, M_2 – mirrors, V – voltage, T_c – cavity round-trip time, T_m – modulation period

cavity axis and blocked by the diaphragm. The losses of the light are high and the transmission of the EOD–diaphragm setup is low. When $V=0$, the light travels along the cavity axis, its losses on the diaphragm are minimal, and transmission of the modulator is maximal. As a result, due to variations in voltage with the frequency $1/nT_c$, modulator transmission windows having duration $\tau_m \ll T_c$ and separated in time by $nT_c/2$ are formed. At the moment the first transmission window appears, a seed pulse of duration $\tau \sim \tau_m$ starts to be formed in the cavity from the amplified spontaneous emission. During successive round-trips in the cavity, this pulse is being amplified in the active medium and shortened due to the passes (with the frequency $1/T_c$) through the modulator transmission windows. In the output of the laser, there appears a train of short pulses which are separated in time by $nT_c/2$.

3. Model of the laser

For the purpose of numerical investigation of generation of a pulse in a XeCl laser with an EOD, a travelling-wave model of the laser, similar to the model of a KrF laser with an EOD presented in [12], has been applied replacing the equations for interaction of radiation with the KrF medium with adequate equations for the XeCl medium. The latter have been taken from [17]. According to [12], [17], the basic set of equations describing generation of a pulse in a XeCl laser with an EOD has the form:

$$\frac{dN_{B0}(z,t)}{dt} = -\frac{N_{B0}-\Theta_0 N_B}{\tau_v} - \frac{N_{B0}-\Theta_B(N_{B0}+N_{C0})}{\tau_{BC}} - \frac{N_{B0}}{\tau_{B0}} - \left[N_{B0}\sum_{v'=0}^{4}\sigma_{0v'}(\omega_0) - \sum_{v'=0}^{4}\sigma_{v'0}(\omega_0)N_{Xv'}\right](I^+ + I^-), \tag{1}$$

$$\frac{dN_{C0}(z,t)}{dt} = -\frac{N_{C0}-\Theta_0 N_C}{\tau_v} - \frac{N_{C0}-\Theta_C(N_{B0}+N_{C0})}{\tau_{BC}} - \frac{N_{C0}}{\tau_{C0}}, \tag{2}$$

$$\frac{dN_B(z,t)}{dt} = \alpha R - \frac{N_B-\Theta_B(N_B+N_C)}{\tau_{BC}} - \frac{N_B}{\tau_B} - \left[N_{B0}\sum_{v'=0}^{4}\sigma_{0v'}(\omega_0) - \sum_{v'=0}^{4}\sigma_{v'0}(\omega_0)N_{Xv'}\right](I^+ + I^-), \tag{3}$$

$$\frac{dN_C(z,t)}{dt} = \beta R - \frac{N_C-\Theta_C(N_B+N_C)}{\tau_{BC}} - \frac{N_C}{\tau_C}, \tag{4}$$

$$\frac{dN_{Xv'}(z,t)}{dt} = -\frac{N_{Xv'}-\Theta_{v'}N_X}{\tau_{v'}} - \frac{N_{Xv'}}{\tau_{Xv'}} + [\sigma_{0v'}(\omega_0)N_{B0} - \sigma_{v'0}(\omega_0)N_{Xv'}](I^+ + I^-), \tag{5}$$

$$\frac{dN_X(z,t)}{dt} = -\frac{N_X}{\tau_X} + \frac{N_B}{\tau_B'} + \frac{N_C}{\tau_C'} + \left[N_{B0}\sum_{v'=0}^{4}\sigma_{0v'}(\omega_0) - \sum_{v'=0}^{4}\sigma_{v'0}(\omega_0)N_{Xv'}\right](I^+ + I^-), \tag{6}$$

$$\pm\frac{\partial I^{\pm}(z,t)}{\partial z} + \frac{1}{c}\frac{\partial I^{\pm}(z,t)}{\partial t} = \left[N_{B0}\sum_{v'=0}^{4}\sigma_{0v'}(\omega_0) - \sum_{v'=0}^{4}\sigma_{v'0}(\omega_0)N_{Xv'}\right]I^{\pm} - \rho I^{\pm} + \Phi, \tag{7}$$

$$I^+(z=0,t) = R_1 I^-(z=0,t), \tag{8}$$

$$I^-(z=L_c,t) = R_2 I^+(z=L_c,t), \tag{9}$$

$$I^+(z=z_D+0,t) = T_D^+(t) I^+(z=z_D-0,t), \tag{10}$$

$$I^-(z=z_D-0,t) = T_D^-(t) I^-(z=z_D+0,t) \tag{11}$$

where I^+ and I^- are the photon fluxes in the positive and negative directions of the cavity axis z, respectively; N_B, N_C and N_X are the populations of B, C and X states of a XeCl molecule, respectively; N_{B0} and N_{C0} are the populations of vibrational levels with the vibrational quantum number $v=0$ in the B and C states, respectively; $X_{v'}$ is the population of vibrational levels with the quantum number $v'=0, 1 \dots 4$ in the X state; τ_v and $\tau_{v'}$ are the vibrational relaxation times of low-lying levels in the B, C and X states; τ_{BC} is the time of collisional mixing between the B and C states; τ_{B0}, τ_{C0} and $\tau_{Xv'}$ are the decay times of the B_0, C_0 and $X_{v'}$ levels, respectively; τ_B, τ_C and τ_X are the decay times of the B, C and X states, respectively; τ'_B and τ'_C are the times of transitions $B \to X$ and $C \to X$, respectively; $\sigma_{0v'}(\omega_0)$ and $\sigma_{v'0}(\omega_0)$ are the cross-sections for the $B_0 \to X_{v'}$ and $X_{v'} \to B_0$ transitions, respectively, at the carrier frequency ω_0; αR and βR $(\alpha+\beta \leqslant 1)$ are the rates of formation of XeCl molecules in the B and C states, respectively; Θ_B and Θ_C are the Boltzmann coefficients for the B and C states, respectively; Θ_0 and $\Theta_{v'}$ are the Boltzmann coefficients for vibrational levels $v=0$ in the B and C states and for the v' levels in the X state, respectively; $\Phi = \varkappa^2 N_{B0}/4\tau^s_{B0}$ is the term describing spontaneous emission; τ^s_{B0} is spontaneous lifetime of the B_0 level; $\varkappa$ is the radiation divergence; ρ is the coefficient of losses in the medium; R_1 and R_2 are the reflectivities of the M_1 and M_2 mirrors, respectively; $T_D^+(t)$ and $T_D^-(t)$ are the D diaphragm transmissions in the positive and negative directions of the cavity axis, respectively; $z=0$, $z=L_c$ and $z=z_D$ are the coordinates of the M_1 and M_2 mirrors of the D diaphragm, respectively $(L_c - z_D \ll L_c)$; and c is the speed of light.

It was assumed in the calculations that the $R(t)$ function describing the pumping rate has the form $R(t) = R_0 \exp[-\ln 2(2t/T_{pump})^4]$, whereas numerical values of the medium parameters (cross-sections, relaxation times, *etc.*) were taken according to [17] (see Table II in [17]). To determine the $T_D^+(t)$ and $T_D^-(t)$ transmissions, a special numerical procedure described in [12] was applied. It employs, in particular, the integral Fresnel–Kirchhoff formula to determine variations in spatial distribution of radiation after passing the diaphragm as well as uses the dependence of the beam deflection angle on the voltage applied to the EOD. This procedure enables sufficiently accurate determination of the losses introduced by the modulator at each moment of the calculations [12].

The numerical simulations of the laser operation were performed for a fixed layout of the cavity elements, at the diaphragm aperture $d_D = 1$ mm and the cavity length $L_c = 1$ m. The case of an EOD driven with a sine wave of voltage as well as the case of an EOD driven with a square wave were considered.

4. Results of numerical simulation and discussion

4.1. The XeCl laser with a sine-wave driven EOD

In the case of an EOD driven with a sine wave, the operation of the EOD as a cavity-loss modulator in the laser of a fixed configuration can be characterized by two parameters: the modulation period T_m and the maximum angle of the beam deflection Θ_m, *i.e.*, the angle between the axis of the cavity and the axis of the beam when the voltage at the EOD reaches the maximum value ($V = V_0$). The laser operation is also determined by properties of the amplifying medium and static losses in the system. Thus, for a fixed kind of the active medium, the most significant additional parameters characterizing the system are: the gain-length product g_0L (g_0 is the small-signal gain coefficient at the maximum of the pumping pulse and L is the length of the amplifier), the gain duration identified in the model with the effective time of pumping T_{pump} and the output-coupler reflectivity R_2 representing the main source of static losses. Thereby, fundamental features of the process of USP generation in the system considered can be revealed by investigation of the influence of the above five parameters on this process.

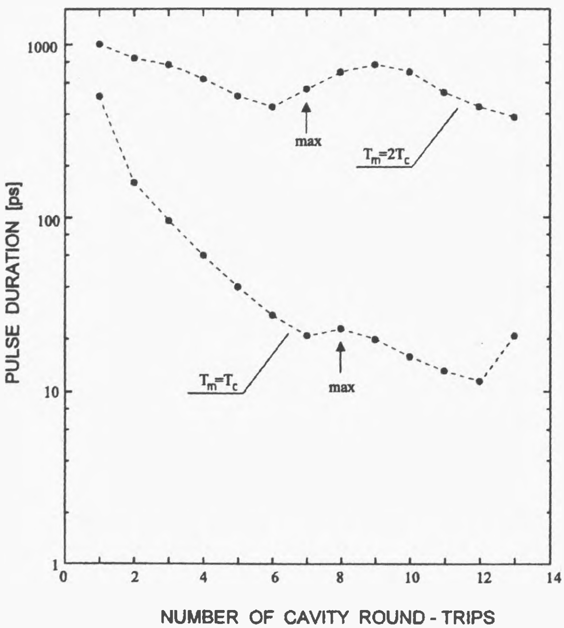

Fig. 2. Pulse duration vs. the number of cavity round-trips at two different values of the T_m/T_c ratio. The EOD is driven with a sine-wave voltage. The points indicated with arrows correspond with the number of round-trips at which the pulse peak intensity reaches a maximum value. $T_{pump} = 50$ ns, $\Theta_m = 1$ mrad, $g_0L = 4$, $R_2 = 0.1$

Figure 2 presents the evolution of the pulse duration τ (FWHM) during successive round-trips in the cavity of the laser with the sine-wave driven EOD. The points indicated with arrows correspond with the numbers of round-trips at which the pulse peak intensity reaches a maximum value. It can be noticed that the duration of the strongest pulse at $T_m = T_c$ is much shorter than the one in the case where $T_m = 2T_c$. This results from faster voltage variations in the vicinity of $V = 0$, and thereby from shorter transmission window of the modulator at $T_m = T_c$. Nonmonotonic dependence of τ on the number of cavity round-trips N, particularly distinct at $T_m = 2T_c$, is related to nonlinearity (saturation) of the medium gain leading to shifting of the pulse peak towards the pulse begining and, as a result, to propagation of the pulse peak with a speed u_p exceeding the speed of light c. This leads to the situation where the peak of the pulse circulating in the cavity not always hits the maximum of the window's transmission, the consequence of which can be a decrease in the pulse-peak intensity and broadening of the pulse. The effect of shifting the pulse peak is one of important factors limiting the minimum duration and the maximum power of the pulse in the system considered and, in addition, can lead to deformations of the pulse shape.

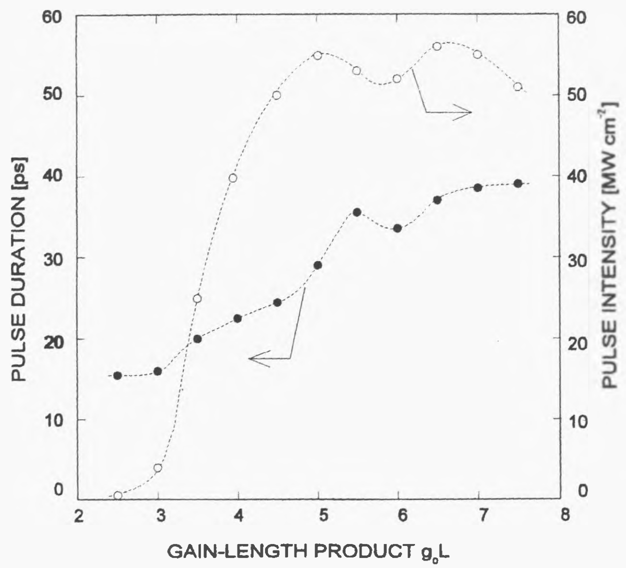

Fig. 3. Peak intensity and duration of a pulse vs. gain-length product for the case of the EOD driven with a sine wave. $T_m = T_c$, $T_{pump} = 50$ ns, $\Theta_m = 1$ mrad, $R_2 = 0.1$

Unfavourable influence of the pulse propagation with the speed $u_p > c$ on the pulse duration is the stronger, the higher the gain of the system. This is particularly evident in Fig. 3 presenting the dependence of the pulse duration τ and peak intensity I_p on g_0L for the case $T_m = T_c$. The dependences shown in this figure, as well as in further figures, relate to parameters of one of the pulses in the train emitted from the laser, namely the pulse of a maximum intensity. An increase in g_0L leads to elongation of the pulse duration, whereas its peak intensity increases distinctly with g_0L only in a limited range of values of this parameter. A similar tendency can be observed at increasing the net gain (gain minus static losses) by an increase in the

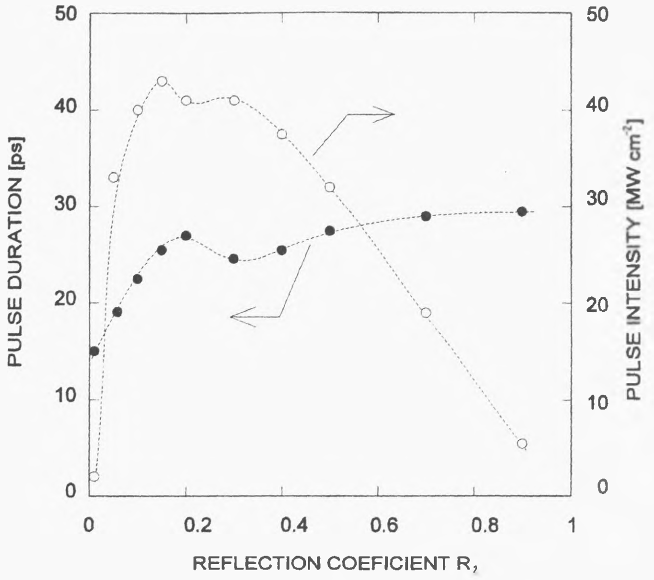

Fig. 4. Peak intensity and duration of a pulse vs. the output-coupler reflectivity for the case of the EOD driven with a sine wave. $T_m = T_c$, $T_{\text{pump}} = 50$ ns, $\Theta_m = 1$ mrad, $g_0L = 4$

reflectivities of the mirrors (Fig. 4). Thus, to obtain pulses of a minimum duration, one should apply systems with a relatively low net gain. In general, the influence of the gain and static losses on duration of the pulse generated is, however, less significant than the influence of modulator parameters and the pumping time of the laser.

One parameter especially strongly influencing the duration and power of the pulse generated is the maximum deflection angle Θ_m. The $\tau(\Theta_m)$ and $I_p(\Theta_m)$ dependences are presented in Fig. 5. The pulse duration varies approximately according to the formula $\tau \approx a/\Theta_m$ (a is the scaling factor). However, the shortening of the pulse with an increase in Θ_m is not accompanied by monotonic increase in the pulse peak intensity – which could have been expected – but, in the region of sufficiently high values of Θ_m, the $I_p(\Theta_m)$ dependence decreases distinctly. This is mainly the result of the above-mentioned effect of propagation of the pulse in the medium with the speed u_p higher than c.

The parasitic influence of the effect of the pulse-peak propagation with the speed $u_p > c$ on the pulse duration and its power can be partially neutralized by an adequate detuning of the modulation period T_m from T_c. This is shown in Fig. 6 presenting the pulse duration and peak intensity as a function of the detuning $\delta = (T_m - T_c)/T_c$. At an optimum detuning, the duration is twice shorter and the peak intensity is about five times higher than in the case of precise resonance.

A significant influence on parameters of the maximum pulse generated from the laser originates from the pumping time T_{pump} (the gain duration). However, due to propagation of the pulse peak with velocity $u_p > c$, the trace of the $\tau(T_{\text{pump}})$ and

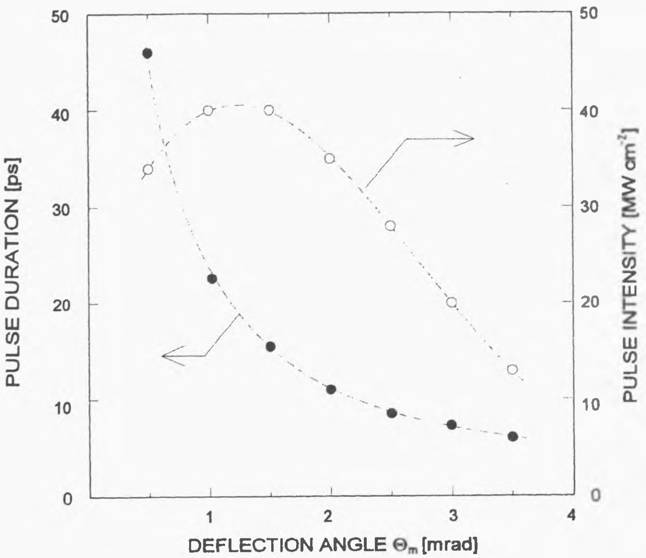

Fig. 5. Dependence of the peak intensity and duration of a pulse on the maximum deflection angle for the case of the EOD driven with a sine wave. $T_m = T_c$, $T_{\text{pump}} = 50$ ns, $g_0L = 4$, $R_2 = 0.1$

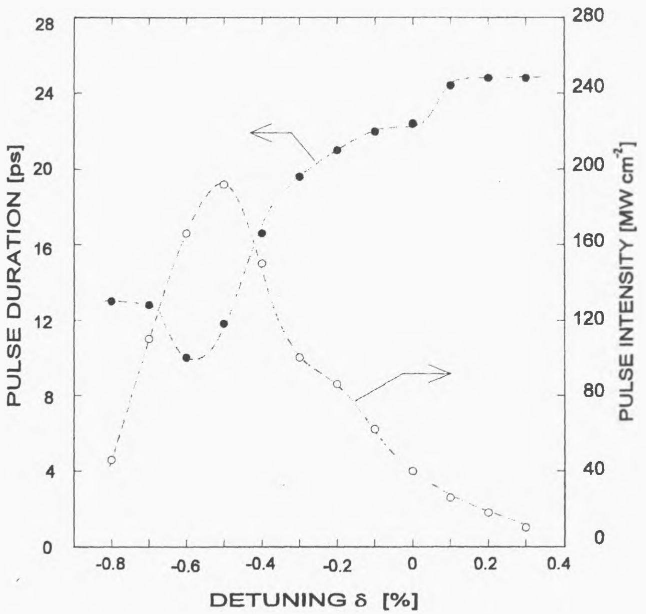

Fig. 6. Influence of detuning $\delta = (T_m - T_c)/T_c$ on the peak intensity and duration of a pulse for the case of the EOD driven with a sine wave. $T_m \approx T_c$, $T_{\text{pump}} = 50$ ns, $\Theta_m = 1$ mrad, $g_0L = 4$, $R_2 = 0.1$

$I_p(T_{\text{pump}})$ dependences is deeply influenced by the detuning δ. The dependence of the pulse parameters on the pumping time of the XeCl laser, at the detuning $\delta = -0.6\%$, is illustrated in Fig. 7. As can be seen, an increase in T_{pump} causes a rapid growth

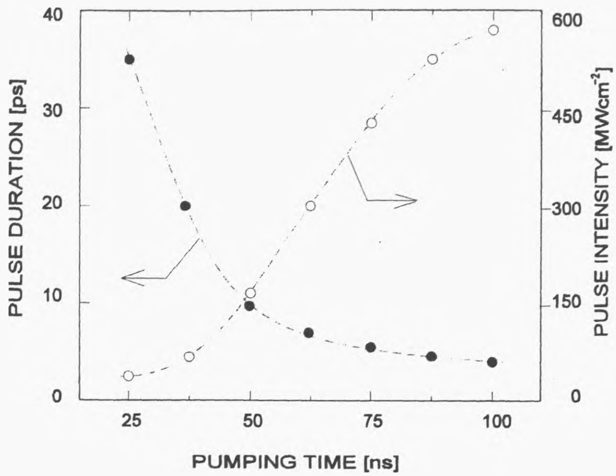

Fig. 7. Dependence of the peak intensity and duration of a pulse on the pumping time of the laser. The EOD is driven with a sine wave. $\Theta_m = 1$ mrad, $g_0L = 4$, $R_2 = 0.1$, $\delta = -0.6\%$

of the pulse peak power and shortening of its duration roughly as $(T_{pump})^{-b}$, where $1 < b < 2$. However, when no detuning is provided, the shortening of the pulse and the increase in its power with an increase in T_{pump} occur only in a limited range of the pumping time and the pulse shortening is relatively low. Therefore, to obtain extreme values of the pulse parameters, particularly at elongated pumping times of the laser, selection of an optimum value of the detuning is very important. In an actual laser system, selection of this value should not present difficulties, since the $\tau(\delta)$ and $I_p(\delta)$ distributions are sufficiently broad even for $T_{pump} \sim 100-200$ ns.

4.2. The XeCl laser with a square-wave driven EOD

An unquestionable advantage of modulators with an EOD driven by a sine-wave voltage is the ease of production of such a wave, particularly by means of commercially available RF generators. Such a way of driving an EOD, however, has a drawback consisting in the fact that the effective voltage-switching time in the vicinity of $V = 0$, τ_s, is closely related to the period of the wave T_m and consequently to the cavity round-trip time T_c: $\tau_s \approx T_m/6 \approx nT_c/6$, where $n = 2, 1, 1/2, \dots$. Due to the fact that practically the most interesting case seems to be the one where $n = 1$ (at $n \leqslant 1/2$, the number of pulses circulating in the cavity is too large – see Sec. 2), we obtain $\tau_s \approx 1.1$ ns at a typical cavity length $L_c = 1$ m. Thus the effective voltage-switching time is relatively long. Therefore, to obtain sufficiently short transmission windows of the modulator in this case, one should provide relatively wide deflection angles Θ_m and, consequently, adequately high amplitudes of the voltage wave driving the EOD. This inconvenience can be considerably weakened by using a square wave of voltage to drive the EOD. Such kind of the voltage wave (produced by means of a cable-line generator) was applied, in particular, to drive a Pockels cell in a ruby laser and a CO_2 laser in the works [18], [19]. In the case of a square wave, the effective voltage-switching time near $V = 0$ can be varied irrespective of the modulation period T_m, for instance, by an adequate selection of electric parameters of the modulation system. Thus, the effective switching time τ_s is, in this case, an additional free parameter characterizing the voltage wave.

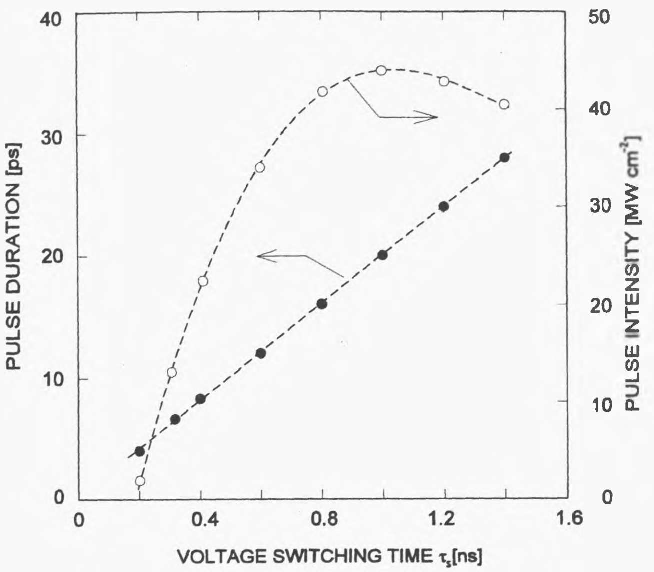

Fig. 8. Influence of the voltage switching time on the peak intensity and duration of a pulse for the case of the EOD driven with a square wave. $T_m = T_c$, $T_{pump} = 50$ ns, $\Theta_m = 1$ mrad, $g_0L = 4$, $R_2 = 0.1$

To simulate the operation of the XeCl laser with an EOD driven by a square wave of voltage, we assumed that the voltage rose and fell exponentially with the effective ($1/e$) switching time τ_s. The influence of τ_s on parameters of a maximum pulse in the pulse train generated from the laser is presented in Fig. 8. The pulse duration varies approximately linearly with τ_s but, at short switching times, the pulse peak intensity decreases rapidly with τ_s decreasing. Thus, with the lack of suitably selected detuning of T_m from the resonance, the shortening of a pulse occurs at the sacrifice of a considerable decrease in the pulse power in this region of τ_s. Like in the case of a sine wave, this situation can be improved by optimization of the detuning δ.

Figure 9 presents the dependence of duration and peak intensity of a pulse on the maximum deflection angle Θ_m, for two different switching times τ_s. Comparing this figure with Fig. 5, one can notice a remarkable similarity between the plots presented in these figures, particularly for $\tau_s = 1$ ns (the $I_p(\Theta_m)$ dependence for $\tau_s = 0.4$ ns is also nonmonotonic, but this can be revealed only after broadening the range of Θ_m variation towards lower values). In the case where $\tau_s = 1$ ns, the consistency of $\tau(\Theta_m)$ and $I_p(\Theta_m)$ dependences for the sine wave and the square wave is not only qualitative but to a large degree also quantitative. This is not accidental if we take into account that the effective switching time of voltage in the sine wave (Fig. 5) amounts to $\tau_s \approx 1.1$ ns, thus it is close to the value of τ_s for the square wave

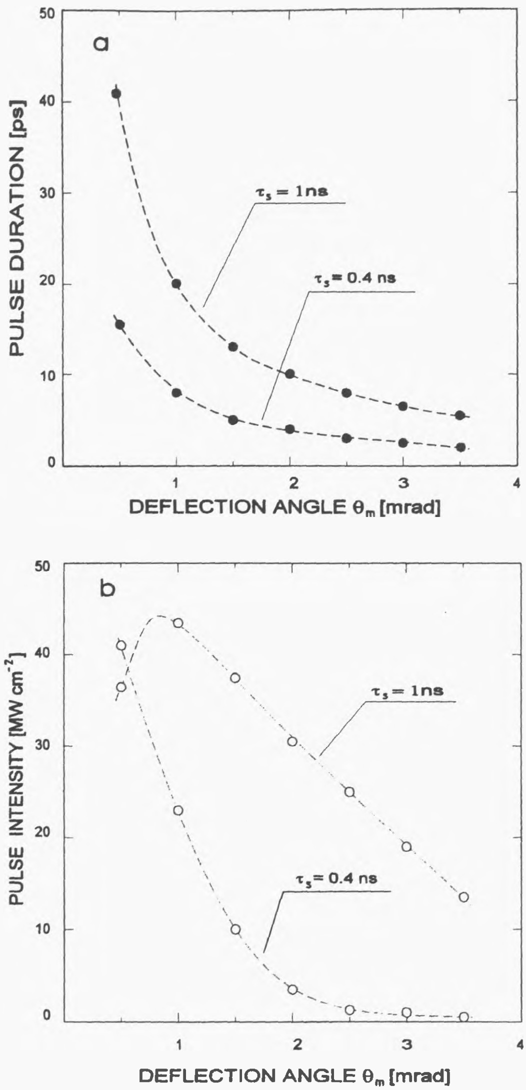

Fig. 9. Pulse duration (a) and pulse peak intensity (b) vs. the maximum deflection angle for the case of square-wave driven EOD. $T_m = T_c$, $T_{pump} = 50$ ns, $g_0L = 4$, $R_2 = 0.1$

(Fig. 9). A quite similar agreement of the results for EODs driven by sine and square waves with close values of τ_s can be observed also in the case of the curves representing the dependences of τ and I_p on other parameters of the system (δ, g_0L, *etc.*), which is shown in Figs. 6 and 10 as an example. On this basis, one can conclude that the decisive factor for the pulse duration and power is the effective voltage-switching time in the vicinity of $V = 0$ (with other parameters fixed), whereas it is not very significant whether the course of voltage has a sine or square form. It is worth to emphasize, however, that thanks to the possibility of obtaining lower values

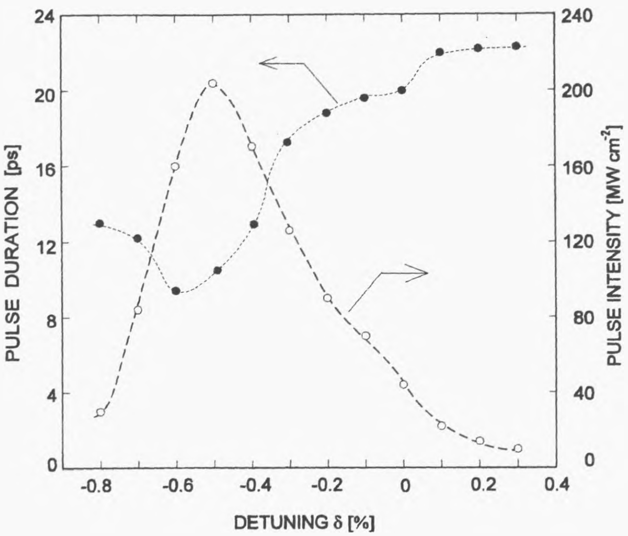

Fig. 10. Influence of detuning $\delta = (T_m - T_c)/T_c$ on the peak intensity and duration of a pulse for the case of square-wave driven EOD. $T_m \approx T_c$, $T_{pump} = 50$ ns, $\Theta_m = 1$ mrad, $g_0 L = 4$, $R_2 = 0.1$, $\tau_s = 1$ ns

of τ_s in the case of a square wave, the same duration of a pulse as in the case of a sine wave can be obtained at a lower amplitude of the voltage (narrower Θ_m – see Fig. 9a). On the other hand, at the same voltage amplitude for both kinds of waves, the square wave creates the possibility of production of a pulse with shorter duration (Fig. 9a).

5. Conclusions

The numerical investigations carried out in this work allowed us to formulate the following conclusions:

– Effective generation of an ultrashort pulse in a XeCl laser is possible at driving the EOD with both square and sine wave of voltage.

– At a fixed pumping time of the laser, the decisive factors for the pulse duration are first of all the parameters characterizing operation of the EOD, whereas the gain and static losses of the system are of less significance. The pulse is the shorter, the wider the maximum deflection angle and the shorter the effective voltage switching time at the deflector.

– Parameters of a pulse do not practically depend on whether the EOD is driven with a sine or a square wave of voltage, provided that the effective voltage switching time is the same in both cases.

– A significant parasitic influence on duration and power of a pulse originates from the effect of pulse-peak propagation in the amplifying medium with the speed $u_p > c$ caused by transient saturation of the gain. The role of this effect can be reduced by decreasing the net gain of the system and slight detuning of the modulation period T_m from the resonance so as T_m would be a little bit shorter than the cavity round-trip time T_c. At a suitable selection of the detuning, the pulse duration decreases rapidly with an increase in the pumping time of the laser T_{pump}.

– At $T_{pump} \sim 50-100$ ns, one can obtain pulses of duration of the order of a few picoseconds, *i.e.*, pulses two orders of magnitude shorter than in the case of mode locking with an acoustooptic modulator.

The results obtained in this work for a XeCl laser with an EOD are similar to those obtained in the case of a KrF laser with an EOD [12]. The differences are not of qualitative character but are only quantitative: the pulses from the XeCl laser are from several to some tens percent longer and their peak powers are commonly one-third to one-second of those of the pulses from the KrF laser. This implies a weak (not primary) dependence of the duration of a pulse generated on the kind of the active medium of the laser in the range of pulse duration considered (*i.e.*, in conditions of incoherent interaction of a pulse with the medium). This allows us to believe that FML using an EOD can be an efficient method for generation of ultrashort pulses not only in excimer rare-gas halide lasers (KrF, XeCl, XeF, KrCl) but also in other short-gain-duration broad-bandwidth lasers.

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References

[1] *Ultrashort Laser Pulses and Applications*, [Ed.] W. Kaiser, Springer-Verlag, Berlin, Heidelberg, New York 1988.
[2] Spielman C., Curley P. F., Brabec T., Krausz F., IEEE J. Quantum Electron. **30** (1994), 1100.
[3] Shay T. M., Sze R. C., Maloney M., Figueira J. F., J. Appl. Phys. **64** (1988), 3758.
[4] Grasyuk A. Z., Efimovskii S. V., Zhigalkin A. K., Karev Yu. I., Kurbasov S. V., Kvantovaya Electron. **17** (1990), 35 (in Russian).
[5] Fedosejevs R., Offenberger A. A., IEEE J. Quantum Electron. **21** (1985), 1558.
[6] Bourne O. L., Alcock A. J., Appl. Phys. **B 36** (1985), 181.
[7] Kurnit N. A., Thomas S. J., IEEE J. Quantum Electron. **25** (1989), 421.
[8] Alimpiev S. S., Vartapetov S. K., Veselovsky I. A., Likhansky S. V., Obidin A. Z., Opt. Commun. **96** (1993), 71.
[9] Badziak J., Dubicki A., Opt. Quantum. Electron. **24** (1992), 1381.
[10] Badziak J., Dubicki J., Piotrowski J., Opt. Commun. **91** (1992), 147.
[11] Badziak J., Jabłoński S., Opt. Commun. **103** (1993), 277.
[12] Badziak J., Jabłoński S., IEEE J. Quantum Electron. **33** (1997), 490.
[13] Lee B. Y., Kobayashi T., Morimoto A., Sueta T., IEEE J. Quantum Electron. **28** (1992), 1739.
[14] Houtman H., Cheuck A., Elezzabi A. Y., Ford J. E., Laberge M., Liese W., Stuart G. C., Zhu Y., Rev. Sci. Instrum. **64** (1993), 839.
[15] Vankov A. B., Kozlov A. A., Chizhov S. A., Yashin V. E., Quantum Electron. **25** (1995), 556.
[16] Badziak J., Chizhov S. A., Kozlov A. A., Makowski J., Paduch M., Tomaszewski K., Vankov A. B., Yashin V. E., Opt. Commun. **134** (1997), 495.
[17] Badziak J., Opt. Quantum Electron. **28** (1996), 1139.
[18] Houtman H., Meyer J., J. Appl. Phys. **54** (1985), 4892.
[19] Houtman H., Meyer J., J. Appl. Phys. **61** (1987), 843.

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