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Combined mode locking in solid-state lasers with self-focusing and synchronous pumping

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Abstract. A new method is proposed for mode locking in solid-state lasers, based on the use of synchronous pumping in systems with self-focusing of radiation on the active element. The method makes it possible to dispense with the external devices for initiating generation of ultrashort pulses. The duration of the output pulses, governed by the response time of the almost instantaneous self-focusing mechanism, approaches the minimum possible value. The permissible mismatch between the lengths of the main and pump lasers exceeds the traditional values by three orders of magnitude.

Passive modulators of laser radiation based on nonresonant nonlinearities are used widely in the generation of subpicosecond and femtosecond pulses. The widely used systems include, for example, those utilising the dependence of the phase properties of radiation on its intensity. This dependence appears because of the third-order nonlinearities of optical components of a laser, which are responsible for the appearance of self phase modulation of the field [1, 2], or because of the optical Kerr effect [3, 4].

Self-focusing is very attractive as a method of laser mode locking. Laser systems in which ultrashort pulses are generated as a result of self-focusing of the field on the active element are the most promising for the mastering of the femtosecond range of pulse durations and the terawatt range of the optical pulse powers [5–12]. The mechanism of mode locking by self-focusing is based on the variation of the diffraction losses in a laser cavity with the intensity of the output field because of a nonlinear change in the mode radius and in the wavefront curvature during passage through a nonlinear component. A suitable selection of the parameters of a laser system can ensure that this variation is typical of the transmission of an instantaneous-response saturable absorber, used traditionally as a passive modulator of radiation in mode-locked lasers.

However, the third-order nonlinear effects in traditional active media are very weak, so that mode locking has to be initiated by additional active or passive modulators or by the use of strongly nonlinear optical components, which would complicate the cavity configuration [13].

We shall propose a new method of combined mode locking by self-focusing of the field in the active medium of a synchronously pumped laser. This method combines the simplicity of realisation, low-pump powers, and a high reproducibility of the lasing, on the one hand, with the advantages of the methods of mode locking by self-focusing, on the other. A fluctuation model of stimulated emission from a solid-state laser and a self-consistent analysis of the fundamental eigenmode of a four-mirror cavity with a nonlinear active medium and a stop was used by us to investigate effective mode locking in such a laser and to compare the results with those for a cw laser with mode locking by self-focusing.

Fig. 1 shows schematically the cavity of a laser with combined mode locking. A synchronously pumped four-level active medium of length z is characterised by the absorption and emission cross sections $\sigma _{14}$ and $\sigma _{12}$, respectively, and by the maximum gain $\gamma _{0}$. This medium is located between two spherical mirrors (1 and 2) with identical focal lengths f. The lengths of the 'highly reflecting' and output arms of the cavity are a and c, respectively. At a distance $d$ from the output mirror (4) there is a stop (5), with an aperture diameter D, which creates diffraction losses in the cavity.

If the parameters of the fundamental Gaussian cavity mode are not affected by a round trip through the cavity, we can find the self-consistent parameters of a cavity eigenmode at the output mirror:

$$\frac{1}{R} = \left( P - \frac{xy}{g^2} - \frac{iQ}{g} \right)^{1/2} \left[ d^2p + d\left( 1 - \frac{ie}{g} \right)Q \right] + \left( 1 + \frac{ie}{g} \right)^2 \left( \frac{xy}{g} \right)^{-1/2}, \tag{1}$$

where $\rho$ is the beam radius; R is the radius of curvature of the wavefront; $P = S(b - 2f)$; $S = (a - f)(b - f) - af$; $b = b_1 + b_2 + z/n$; $n$ is the refractive index of the active medium; $Q = Sx + (b - 2f)$; $x = (c - f)^2 - cf; y = [(a - f)b - af](c - f) - cf(a - f); g = kD^2/4; k$ is the wave number.

In the case of self-focusing the paraxial approximation [14] allows us to write down the mode parameters at
the output from the active medium:

\[ \rho = [(C_2 + C_3)^2 + C_4] / C_1, \quad R = \rho / (C_2 + C_3), \quad (2) \]

where \( C_1 = \rho_0 / R_0^2 + C_2 / \rho_0; \ C_2 = \rho_0 / R_0; \ C_3 = 1 - 2 \beta \rho_0 \rho_0^2; \)
\( \beta = k n_2 / 2 n_2, \ \alpha = \) the nonlinear refractive index of the active medium; \( \rho_0, \ R_0, \ \) and \( \rho_0 \) are the parameters and the amplitude of the beam before it enters the active medium.

An analysis of the evolution of a beam during its round trip through the cavity, carried out with account taken of self-focusing, demonstrates that the diffusion losses caused by the aperture stop decrease with increase in the intensity of the radiation field in the active medium near the upper limits of the stability regions of the cavity, which are deduced from Eqn (1) on the assumption that \( 1 / g = 0 \) (Fig. 2). The upper part of Fig. 2 is preferable from the point of view of mode locking, because in that part the initial diffraction losses are lower than in the lower part, so that the threshold for the generation of ultrashort pulses is less.

![Figure 2. Stability regions of the investigated cavity in the absence of a stop (\( f = 5 \) cm, \( z = 1 \) cm, \( b_4 = 4 \) cm, \( D = 0.1 \) cm, \( d = 1 \) cm, \( c = 75 \) cm).](image)

We carried out a numerical simulation of lasing on the basis of a fluctuation model developed in Refs [2] and [16].

We considered the evolution of the temporal profile of the lasing field during its passage through the medium and through a spectral filter characterised by a delay time \( t_\text{d} \).

This delay time was inversely proportional to the spectral width of its pass band. We took account of the nonlinear diffraction losses caused by the stop and of the linear losses \( \gamma \) at the output mirror. We postulated that the initial field was in the form of spontaneous noise with the Lorentzian spectral profile, governed by the correlation time \( t_\text{corr} \), and with a transverse distribution corresponding to the fundamental normal mode of the cavity found with the aid of Eqn (1). We also assumed that throughout the lasing time the transverse distribution of the mode remained Gaussian so that at each moment of the local time \( t \) the field transformation should be governed only by the field intensity and by the parameters of the Gaussian beam.

The dynamics of amplification in the active medium was described, in accordance with Ref. [16], by the equation

\[ \frac{\partial x}{\partial t} = I_p \sigma_{14} (x_m - x) - \frac{x}{T_{31}} - \sigma_{12} / x, \quad (3) \]

where \( T_{31} \) is the relaxation time of the excited state; \( I \) is the lasing photon flux; \( I_p \) is the pump photon flux. It was assumed that pumping is provided either by a steady flux \( I_0 \) or by a train of Gaussian pulses with a peak photon flux \( I_0 \) and duration \( T_p \). The effects which appear because of incomplete spatial overlap of the pump and lasing beams ("soft" aperture case) were ignored. Concentration of 99% of the output radiation energy in one cavity period \( T_{\text{cav}} \) in a single pulse in a time interval at least \( 200 T_{\text{cav}} \) (when the total lasing time was \( 2 \times 10^4 T_{\text{cav}} \) served as the criterion of effective mode locking.

Mode locking solely as a result of synchronous pumping in the absence of self-focusing (zone 2, \( n_2 = 0 \)) is also possible in this system. Since the cross sections \( \sigma_{12} \) for traditional solid-state active media are relatively small, mode locking by synchronous pumping requires higher values of \( U_p \) [17, 18]. For this reason, the corresponding zone is located at normalised pump fluxes \( U_p \), which are three orders of magnitude higher than similar values for passive mode locking by self-focusing when the pumping is continuous. As expected, the zone of effective mode locking occupies a relatively wide range of \( b_4 \), corresponding to the stability region of the cavity (Fig. 2). In our case the diffraction losses in this zone do not exceed 50% and are lowest near \( b_4 = 6.1 \) cm.

Combined mode locking by self-focusing and synchronous pumping (zone 3 in Fig. 3) is the most interesting. A large part of the corresponding zone lies much lower along the \( U_p \) axis than in the case of mode locking by synchronous pumping alone, and the pump threshold approaches the minimum threshold values of \( U_p \) observed in the case of continuous pumping. The dependence of the threshold flux \( U_{p_t} \) on \( b_4 \) is much smoother than in the continuous pumping case, which should make it easier to tune the system so that it generates ultrashort pulses. The size of the zone along the \( U_p \) axis, corresponding to a fixed value of \( b_4 \), is also considerably larger in the case of combined mode locking. This is evidence of the higher stability of lasing and of the absence of undesirable breakdown of laser action because of the appearance of chaotic multipulse regimes. The stability of combined mode locking is also characterised by permissible values of the relative mismatch between the cavity periods of the main and
pump lasers, which are three orders of magnitude greater than in the case of mode locking by synchronous pumping alone [17].

It is of interest to analyse the behaviour of the ultrashort pulse duration $t_{\text{las}}$ (Fig. 4). In view of the difficulties encountered in ensuring effective gain saturation for ultrashort pulses in solid-state lasers [17, 18], the durations $t_{\text{las}}$ achieved in the synchronous pumping case are always perceptibly greater than in the case of a cw pumping and mode locking by self-focusing (compare curves 2 and 1 in Fig. 4). In the former case, the duration of the laser pulses $t_{\text{las}}$ tends to $(t_p T_p)^{1/2}$ [14], and in the latter case it tends to $2t_p$. Therefore, the minimum duration of the ultrashort pulses emitted in the case of synchronous pumping is governed primarily by the duration of the pump pulses (curve 1 in Fig. 5), whereas in the case of mode locking by self-focusing, the decisive factor is $t_p$.

![Figure 4](image)

**Figure 4.** Dependences of the duration $t_{\text{las}}$ of ultrashort output pulses on the normalised pump photon flux $U_p$ in the case of continuous (1) and synchronous (2, 3) pumping without (2) and with (3) self-focusing, plotted for $b_1 = 6.2$ cm (1, 2) and 6.1 cm (3). The other parameters are the same as in Figs 2 and 3.

The most interesting observation is that, in the case of combined mode locking, the mechanism which determines the pulse duration is specifically self-focusing (curve 3 in Fig. 4), so that synchronous pumping simply initiates mode locking during the initial stages of lasing and ensures stability of the process throughout its duration. A system of this kind is extremely easily tuned to generate ultrashort pulses of $t_{\text{las}}$ on the deviation from the optimal energy of the pump pulses when $b_1$ has the optimal value (Fig. 5). This can be seen by selecting a fixed intensity of the pump pulses and by varying their duration to optimise the pump energy. As pointed out earlier, the duration of the pump pulses $T_p$ is not the factor that limits $t_{\text{las}}$, since in the case of combined mode locking the ‘base’ mechanism is self-focusing and we can expect ultrashort pulse durations which are no longer than the durations obtained from continuously pumped lasers with self-focusing.

It is evident from Fig. 5 (curve 2) that variation of the pump pulse energy by variation of the pump pulse duration $T_p$ by more than one order of magnitude in the range of long pump pulses and, consequently, high pump energies does not result in a perceptible increase in $t_{\text{las}}$ when the peak intensity of the pump pulses is kept constant. However, in the range of short pump pulse durations $T_p$ (low pump energies), when the intensity of the laser pulses is low and self-focusing is undetectable, the duration of the laser pulses is governed primarily by synchronous pumping, i.e. this duration decreases with increase in the pump energy because of an increase in the intensity of the laser pulses and because of the more effective use of the gain. A further increase in $T_p$, in the absence of self-focusing would have increased $t_{\text{las}}$, because use of the much greater gain would have required longer laser pulses. However, this does not occur because of the self-focusing mechanism and the dependence $t_{\text{las}}(T_p)$ is, as pointed out above, practically horizontal.

The most striking result is that a reduction in $T_p$ by more than one order of magnitude, resulting in a proportional reduction in the pump energy, has no significant influence on combined mode locking for pump energies at which mode locking is known to be impossible in the case of cw pumping, irrespective of whether synchronous pumping or self-focusing is used. Hence, we can draw the conclusion that in combined mode locking the process of synchronous pumping acts as a constant ‘seeding’ mechanism which favours strongly the formation of ultrashort pulses.

The proposed method for combined mode locking makes it possible to dispense with active radiation modulators, of the kind used in traditional systems for initiation of the generation of ultrashort pulses. The use of synchronous pumping can reduce significantly the sensitivity of a laser to the precision of adjustment of the geometric dimensions of the cavity needed to ensure effective mode locking by self-focusing. Moreover, synchronous pumping can also enhance considerably the stability of ultrashort pulse generation. These features allow us to hope that the proposed method for combined mode locking of solid-state lasers can ensure very simple (in respect of its realisation), but very efficient generation of stable ultrashort pulses of durations closest to the minimum limit.

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**References**