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Effective self-mode-locking of cw solid-state lasers with a resonant nonlinearity in an additional cavity

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Abstract. A fluctuation model of the operation of a cw solid-state laser with an additional cavity containing a saturable absorber is used to identify the effective self-mode-locking ranges which are closed areas when plotted in terms of the laser parameters. The main features of effective mode locking are related to the behaviour of the transmission of the additional cavity, considered as a function of the field intensity. It is shown that a resonant nonlinearity ensures effective mode locking both in the absence of interferometric matching of the cavity lengths and in the presence of a ‘macromismatch’ of their lengths when the delay of the field from the additional cavity relative to the lasing pulse is comparable with the pulse duration.

Methods for mode locking of cw solid-state lasers based on the use of an additional (nonlinear [1–9] or linear [10, 11]) cavity are now firmly established in systems generating subpicosecond and femtosecond pulses. The main mode-locking mechanism in such systems is the interference of the fields from the main and additional cavities in the presence of a nonlinear phase shift resulting from self-phase-modulation of the laser radiation field: such modulation is due to the presence of a nonresonant third-order Kerr nonlinearity of the optical components in the main or additional cavities. The advantages of such systems include the instantaneous response of the Kerr nonlinearity, whose characteristic time approaches $10^{-15}$ s, and the ability to dispense with the matching of the pass band of a modulator based on an additional cavity and the Kerr nonlinearity to the emission band of a broad-band active medium. Moreover, the process of mode-locking in lasers with an additional cavity and a nonresonant third-order optical nonlinearity is effective in a wide range of intensities and durations of the output pulses, since the discriminating action of such a modulator depends on the ultrashort pulse intensity (in contrast to, for example, ‘saturation’ of a passive switch made of a bleachable absorber, which occurs as the ultrashort pulse intensity rises). All of these factors are why lasers with an additional cavity and nonresonant Kerr nonlinearity have become attractive as sources of high-intensity pulses shorter than 100 fs.

Unfortunately a serious shortcoming of these systems is the need for precise interferometric matching of the lengths of the main and additional cavities throughout the lasing time, which complicates these systems considerably [12]. It has been shown recently that lasing stability can be improved significantly by the use of a resonant nonlinearity in an additional cavity [13–16]. This has led us to use a fluctuation model in a detailed study of the mode locking of cw solid-state lasers with a resonant nonlinearity in an additional cavity.

Our numerical modelling is based on an analysis of repeated transits of the laser radiation field $V(t)$ through a four-level active medium (with a maximum gain of $\sigma_m$, a relaxation time of the excited state of $T_{11}$, and absorption $\sigma_{14}$ and amplification $\sigma_{23}$ cross sections, pumped by a cw field with a photon flux density of $I_n$) and a Fabry–Perot etalon acting as a filter with a characteristic time $t_f$ governing the spectral width of the transmission of the system [17]. In contrast to our earlier treatment [17], we shall assume that the system of coupled cavities represents a three-mirror interferometer (widely used in practice) in which the relationships between the field $V_{k+1}(t)$ in the main cavity at a moment $t$ of the local time during the $(k+1)$-th transit through this cavity, the field $U_{k}(t)$ in the additional cavity, and the field $V_{k}(t)$ in the main cavity during the preceding transit, are described by the following equations [2]:

\[
V_{k+1}(t) = rV_k(t) + (1 - r^2)^{1/2} U_k(t), \\
U_{k+1}(t) = (1 - r^2)^{1/2} V_k(t) - rU_k(t),
\]

where $r$ is the reflection coefficient of the mirror coupling the cavities.

We shall assume that the main and additional cavities may be mismatched in respect of the phase $\phi$ or in respect of the length. The difference between the phases of the fields in the cavities and their time shift relative to one another will be described in the same way as before [2]:

\[
U_k(t) = U_k(t) \exp(-i\phi), \quad U_k(t+Q) = U_k(t),
\]

where $\phi$ is the difference between the phases; $Q \gg \lambda/c$ is the mismatch between the cavity periods; $\lambda$ is the laser radiation wavelength; $c$ is the velocity of light. Lasing is initiated from the amplitude and phase noise radiation with a Lorentzian spectral profile and with a coherence time $t_{coh}$, which is allowed for throughout the lasing time. We shall assume that the additional cavity contains a resonant nonlinearity in the form of an instantaneous-response switch with an initial transmission of 90%, which becomes bleached by a photon flux of density $I_n$. The linear losses in the main cavity are 10%.
The main variable parameters are the normalised pump intensity \( \sigma_\text{av} T_{\text{av}} I_P \) (where \( T_{\text{av}} \) is the period of the main cavity), the phase mismatch between the resonators \( \varphi \), the reflection coefficient \( r \) of the mirror coupling the cavities, the 'macromismatch' \( Q \) of the cavities, and the saturation parameter of the active medium \( \sigma = (\sigma_\text{av} T_{\text{av}} I_P)^{-1} \), which in the case of passive mode locking determines the position of the second lasing threshold. Calculations show that for certain sets of these parameters a system of this kind generates a stable train of high-intensity ultrashort pulses of the kind shown in Fig. 1.

![Figure 1. Evolution of a laser radiation field with the normalised intensity \( I = \sigma_\text{av} T_{\text{av}} |V_k|^2 \) in the presence of a resonant nonlinearity in an additional cavity, calculated for \( \sigma_\text{av} T_{\text{av}} I_P = 0.01 \), \( r = 0.6 \), \( \varphi = 0.1 \pi \), \( \sigma = 1 \), \( c_{\text{in}} = 1.5 \), \( q = 1 \, \text{ps} \), \( c_{\text{av}} = 1 \, \text{ps} \), \( T_{\text{av}} = 1 \, \text{ns} \) (k is the transit number).](image1)

The most interesting analysis is that of the effectiveness of mode-locking in a system with a resonant nonlinearity in the additional cavity. The criterion of effective mode locking is the attainment of the conditions [17] ensuring a high concentration of laser radiation energy in a single最强的

\[ \text{peak} \]

in one cavity period, which then remains stable for a long time. We shall adopt this criterion in considering the behaviour of the ranges of the system parameters that ensure effective mode locking. Fig. 2 shows the regions of effective mode locking in terms of the coordinates representing the pump intensity and the phase mismatch between the cavities. We can see (region 1) that, in contrast to mode locking in a laser with a nonresonant nonlinearity in an additional cavity (see Ref. [17]), a resonant nonlinearity ensures the generation of highly stable trains of ultrashort pulses practically throughout the whole range of the phase mismatch between

\[ \sigma_\text{av} T_{\text{av}} I_P \]

the cavities. It therefore follows that under certain pumping conditions (for the selected parameters, these conditions correspond to \( \sigma_\text{av} T_{\text{av}} I_P = 0.01 \)) it is possible to achieve stable mode locking for practically any value of \( \varphi \). Effective discrimination of the field fluctuations in the additional cavity, because of the resonant nonlinearity, ensures the effectiveness of mode locking in a wide range of \( \varphi \). Above the region of mode locking there is a region of generation of stable trains with an interpulse interval equal to half the cavity period. The upper boundary of the latter region is represented by the dashed curve in Fig. 1 (this should be compared with Ref. [16]). A further increase in the pumping rate makes it possible to generate stable trains of an increasing number of ultrashort pulses per cavity period. This is because the instantaneous response of the absorber in the additional cavity ensures the maintenance of a balance between all the factors responsible for mode locking, even when the repetition frequency of the ultrashort pulses is considerably less than the cavity period.

![Figure 2. Mode-locking regions calculated for \( r = 0.6 \), \( \sigma = 1 \), \( P/\sigma_\text{av} T_{\text{av}} = 0 \) (1) and 0.008 (2) on the assumption that the parameters are the same as in Fig. 1, compared with the region of generation of stable trains of double pulses (bounded by a dashed curve at the top).](image2)

Important special features of the generation of ultrashort pulses in a laser with a resonant nonlinearity in an additional cavity are an increase in the mode-locking threshold and a narrowing of the mode-locking region as \( \varphi \) approaches \( \pi \). Moreover, in the limit \( \varphi \to 0 \) the lasing becomes unstable, in agreement with the experimental results [14, 15]. An example of a train for \( \varphi = 0 \) is shown in Fig. 3. We can see that an output pulse exhibits periodic beats accompanied by the formation of satellites at the leading edge of an ultrashort pulse.

![Figure 3. Evolution of a laser radiation field in the presence of a resonant nonlinearity in an additional cavity when \( \varphi = 0 \) and the other parameters are the same as in Fig. 1.](image3)

These features can be explained qualitatively by an analysis of the interaction of the field from the main cavity with that in the additional cavity. The characteristics of the evolution of the field in the additional cavity can be allowed for by expressing the transmission \( T \) of that cavity in the form

\[ T = |V_{k=1}|^2/|V_{k=1}|^2 \]

for \( U_{k=1} = 0 \) without allowance for the effects of the laser components included in the main cavity. The dependences of \( \partial T/\partial I \) on \( I \) and \( \varphi \), where

\[ L = \sigma_\text{av} T_{\text{av}} |V_{k=1}|^2 \]

are plotted in Fig. 4a. It is evident from this figure that the derivative \( \partial T/\partial I \), representing the effectiveness of the discriminating properties of the system, is maximal near \( \varphi = 0.2 \pi \), which corresponds to a lowering of the threshold and a widening of the mode-locking region. Conversely, the minimum of the derivative near \( \varphi = \pi \) corresponds to an increased mode-locking threshold and to a narrowing of the region where the locking occurs. However,
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with an additional cavity with respect of the laser radiation field, plotted as Figure 4.

\[ \varphi = 0.6 \text{ (a, b) and } \varphi = 0.5 \text{ [17]; } \]

\[ \text{a function of } I \text{ and } \varphi \text{ for systems in which an additional cavity contains a resonant (a, c, d) and nonresonant (b) nonlinearity. The curves are plotted for the normalised coefficient } P/\sigma_2T_{\text{cw}} = 0.5 \text{ [17]; } r = 0.6 \text{ (a, b) and } 0.8 \text{ (c, d); } \pi = 1 \text{ (a, c), 0 (b), and 10 (d).} \]

it should be pointed out that if \( \varphi = 0.2\pi \) the system exhibits strong 'bleaching', i.e. a strong fall of \( \partial T/\partial I \) when the laser radiation intensity rises, which may account for the destabilisation of lasing that occurs also in the presence of a bleachable absorber. All this has the effect that the most effective mode locking, in the sense of the stability of the generation of ultrashort pulses and the maximum size (expressed in terms of the pump intensity) of the mode locking region, is observed near \( \varphi = \pm 0.1\pi \) (Fig. 2).

The relationships governing the behaviour of the mode locking regions can be deduced also from an analysis of the durations \( t_0 \) of the ultrashort pulses averaged over a train (Fig. 5). The ultrashort pulse duration is minimal in the case of the most effective mode locking, corresponding to the maximum size, close to \( \varphi = \pm 0.1\pi \) of the mode-locking region expressed in terms of the pump intensity (curve 1 in Fig. 5): this duration is 7 ps, compared with the minimum possible duration of \( \sim 1 \) ps which is governed by the

characteristic time \( t_\tau = 1 \) ps of the spectral filter. As the effectiveness of the mode-locking decreases as \( \varphi \) approaches \( \pi \), the pulse duration \( t_0 \) rises (curve 2 in Fig. 5). Moreover, within the limits of the mode-locking region, the duration of the ultrashort pulses is maximal near the mode-locking threshold and it decreases as the pumping rate increases. However, at the upper boundary of this region there is some increase in \( t_0 \) because of a lower lasing stability and preferential pumping at the leading edge of the pulse.

It should be pointed out that a nonresonant nonlinearity in an additional cavity can ensure, because of the absence of 'saturation' when the field intensity increases (Fig 4b), a duration \( t_0 \sim t_\tau \), which is even less than for a resonant nonlinearity with an instantaneous response. Nevertheless, calculations show that, in contrast to systems with a resonant nonlinearity, the permissible values of the phase mismatch between the cavities in a system with mode locking due to the Kerr nonlinearity lie in a narrow range: from approximately 1.9\( \pi \) to 2\( \pi \) (Fig. 4b). Moreover, the 'modulation strength', defined by the derivative \( \partial T/\partial I \), is perceptibly less for a nonresonant nonlinearity in an additional cavity than in the case when this nonlinearity is resonant. This is because a resonant nonlinearity establishes certain fixed intermode phase relationships that minimise the losses [19], so that the phase mismatch resulting from the difference between the cavity lengths does not significantly distort the intermode interactions of the fields in the two cavities. The opposite is true of mode locking arising from self-phase-modulation: in this case the locking process depends strongly on the intermode phase relationships, so that a change in the mismatch between the resonator lengths significantly distorts mode locking.

In view of this, it would be interesting to consider the influence of self-phase-modulation in an active medium on the mode locking resulting from a resonant nonlinearity in an additional cavity. Self-phase-modulation with a normalised coefficient \( P/\sigma_2T_{\text{cw}} = 0.008 \), which corresponds to a sample of \( \text{Al}_2\text{O}_3: \text{Ti} 2 \text{ cm long (} \rho = k L_0/n_0; n_0, n_2, \text{ and } L_0 \text{ are, respectively, the linear and nonlinear refractive indices, and the length of the active medium; } k \text{ is the wave number), can be allowed for in the same way as in Ref. [17].} \)

The corresponding region is represented by curve 2 in Fig. 2. As in the case of the traditional process of passive mode-locking, self-phase-modulation reduces the effectiveness of mode locking [20], which causes narrowing (in terms of the pump intensity) of the region where stable trains of ultrashort pulses can be generated.

However, in our case self-phase-modulation also results in stable mode-locking when \( \varphi = 0 \), so that such locking becomes possible for any phase mismatch between the cavities. This is accounted for by the existence of a regime of ultrashort pulse generation solely because of self-phase-modulation when \( \varphi = 0 \). It should be pointed out that in the absence of a resonant nonlinearity in an additional cavity this regime is observed only for \( r > 0.9 \), which in our case may play only an auxiliary role, supplementing the main mode-locking mechanism associated with a resonant nonlinearity.

It is of considerable interest to analyse the coupling between the cavities. The region labelled 1 in Fig. 6 corresponds to a reduced (compared with Fig. 2) coupling because of an increase in \( r \). It is evident from this figure that this reduced coupling increases the threshold and narrows the mode-locking region, so that mode-locking disappears near \( \varphi = \pi \). This is because the field intensity in the additional cavity is insufficient for the effective bleaching of a passive

**Figure 4.** Dependence of the derivative of the transmission of a system with an additional cavity with respect of the laser radiation field, plotted as a function of \( I \) and \( \varphi \) for systems in which an additional cavity contains a resonant (a, c, d) and nonresonant (b) nonlinearity. The curves are plotted for the normalised coefficient \( P/\sigma_2T_{\text{cw}} = 0.5 \) [17]; \( r = 0.6 \) (a, b) and 0.8 (c, d); \( \pi = 1 \) (a, c), 0 (b), and 10 (d).

**Figure 5.** Dependence of the average (over a train) duration of ultrashort pulses on the pump intensity, calculated for the following parameters: \( r = 0.6; \varphi = 0.1\pi \) (1, 3) and \( \pi \) (2); \( Q = 0 \) (1, 2) and 30 ps (3), the other parameters are the same as in Fig. 1.
switch. This is illustrated in Fig. 4c, which demonstrates a considerable reduction in $\partial T/\partial t$ at $r = 0.8$, compared with $r = 0.6$, which leads to deterioration of the discriminating properties of the system.

Figure 6. Mode-locking regions for $r = 0.8$, $\sigma = 1$ (1) and 10 (2); the other parameters are the same as in Fig. 1.

The natural way of increasing the effectiveness of mode locking at high values of $r$ is, in our opinion, the selection of a 'softer' switch with a lower value of $I_s$. The corresponding region is represented by curve 2 in Fig. 6. An increase in $\sigma$ strongly reduces the self-mode-locking threshold and widens the mode-locking region because of an increase in $\partial T/\partial t$ (Fig. 4d). This makes it possible to use 'soft' passive switches in an additional cavity with a large value of $r$ (see Ref. [14]).

Important features of mode locking associated with a resonant nonlinearity in an additional cavity include its stability against a macromismatch $Q$ of the resonator lengths [13, 14]. Fig. 7 shows the mode-locking regions for a widely varying $Q$. An increase in the delay time of the field from the additional cavity, compared with the field from the main cavity, increases the mode-locking threshold and narrows the mode-locking region (regions 1 and 2), and it also increases the duration of the ultrashort pulses (curve 3 in Fig. 5). However, even when the mismatch between the cavity lengths corresponds to a path difference of 9 mm ($Q = 30$ ps), effective mode locking is possible for a wide range of values of the pump intensity and phase mismatch. A comparison of regions 1 and 3 shows that a delay in the field from the additional cavity, compared with the field in the main cavity ($Q > 0$), is preferable to an advance in the field in the additional cavity ($Q < 0$). This is because for $Q < 0$ the field from the additional cavity is superimposed on the leading edge of an ultrashort pulse, which is known to be the least stable part of the output pulse [21].

Our numerical modelling of the operation of a cw solid-state laser with a resonant nonlinearity in an additional cavity thus demonstrates that when there is a mismatch between the cavity lengths the lasing regime is more stable than in systems in which the nonresonant Kerr nonlinearity is used. The laser system considered above is capable of ensuring the generation of stable trains of ultrashort pulses when a wide range of system parameters are used, without the need to control the cavity lengths; the duration of the ultrashort pulses then increases slightly compared with systems in which a nonresonant nonlinearity is used. The system proposed above can be used successfully with fast-response passive switches characterised by low saturation intensities, which are ineffective in a single-cavity laser (for example, they are promising solid-state absorbers based on semiconductor structures). It is shown above that effective self-mode-locking is possible when an additional cavity with a saturable absorber is used in the absence of self-phase-modulation in the laser components. We should mention also that some of the time parameters of the system under consideration differ from those typical of lasers emitting ultrashort pulses. However, calculations demonstrate that the process of self-mode-locking is the same in all these cases if $T_{aw} < 10$ ns, $t_{aw} < 1$ ps, and $t_e < 500$ fs. Moreover, the relative dimensions and positions of the self-mode-locking regions corresponding to different resonator parameters are not affected, even when more realistic time characteristics of the system are considered.

References