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Use of second-harmonic generation in mode locking of continuously operating solid-state lasers

V L Kalashnikov, V P Kalosha, V P Mikhailov, I G Poloiko

Abstract. An analysis is made of effective mode locking in continuously operating solid-state lasers by modulators based on second-harmonic generation. A new type of modulator is proposed in which a radiation field replica, attenuated as a result of harmonic generation, is subtracted interferometrically from the field. In principle, the proposed modulators can ensure more effective mode locking because of optimisation of the initial modulator transmission and because the intensity derivative of the transmission is used. Self-consistent solutions of a system describing continuous generation of ultrashort pulses are obtained and are shown to agree with the results of an analysis of the lasing dynamics based on the fluctuation model.

1. Introduction

Mode locking of continuously pumped solid-state lasers is becoming increasingly popular. The locking is based on instantaneous-response nonresonant nonlinearities, capable of ensuring the generation of subpicosecond and femtosecond pulses. These nonlinearities include the cubic nonlinearity of the polarisation vector responsible for phase self-modulation, self-focusing, stimulated birefringence, and the optical Kerr effect. These nonlinear effects have been used in the construction of instantaneous-response passive modulators for continuously pumped solid-state lasers [1–14]. Effective mode locking by such modulators has been investigated theoretically [15–20].

Extensive opportunities for the generation of ultrashort pulses are provided also by modulators used in solid-state lasers and based on the quadratic nonlinearity responsible for second-harmonic generation (SHG) [21–23]. The main problem hindering the use of SHG in mode locking is the fact that the losses at the fundamental frequency in a crystal with quadratic nonlinearity increase with the intensity, whereas the reverse is required for passive modulation.

This problem can be solved by converting the second-harmonic radiation back to the fundamental frequency. A modulator with such conversion consists of a nonlinear crystal and a dichroic mirror with a high reflectivity at the second-harmonic frequency. The phase characteristics of the modulator are selected so that the fundamental radiation, which is frequency doubled and partly reflected from a mirror during the return trip through the nonlinear crystal, is 'pumped up' at the expense of the second-harmonic field [21]. Such pumping-up increases with the intensity of the second harmonic generated during the first (forward) trip through the crystal. Consequently, the modulator transmission at the fundamental frequency increases with the intensity of the initial field.

We shall report an investigation of the feasibility of increasing the effectiveness of mode locking in continuously pumped solid-state lasers by a modulator which is based on SHG and contains a dichroic mirror. Moreover, we shall show that ultrashort pulses can be generated by continuously pumped solid-state lasers if SHG is used in modulators based on an additional cavity and an antiresonant ring. There is then no need for conversion of the second harmonic back to the fundamental frequency. This approach is particularly attractive in the case of ultrashort pulses, because the shorter the pulse the more difficult it is to satisfy the phase and group matching conditions that ensure a high efficiency of conversion of the temporal profile of the pulses without distortions. In modulators of this type a pulse interferes with its nonlinearly attenuated replica which either arrives from the additional cavity or propagates in the opposite direction along the antiresonant ring. A phase mismatch between the interfering waves, which results in the removal of the nonlinearly attenuated replica, induces amplitude discrimination of the radiation and the intensity of the resultant field increases with an increase in the intensity of the field reaching the modulator.

2. Modulator based on second-harmonic generation in the presence of a dichroic mirror

We numerically modelled the dynamics of operation of a continuously pumped solid-state laser with a modulator based on SHG and containing a dichroic mirror. This modelling was based on the fluctuation model developed in Refs [15, 18]. We analysed the transformation of the time profile of the fundamental-frequency field \( A_0(t, z) \) (\( t \) is the local time, \( z \) is a longitudinal coordinate travelling with the field) by multiple trips across an active medium (maximum gain \( g_m \), absorption cross section \( \sigma_a \), emission cross section \( \sigma_{em} \)) pumped by a photon flux of constant density \( I_p \) [24] and across a Fabry–Perot etalon (group delay time of the field \( t_r \)) acting as a frequency filter. We allowed for the interaction with the SHG-based modulator.

The transformation of the field in the modulator was described by a system of equations for the fields representing the first (\( \omega \)) and second (2\( \omega \)) harmonics [24]:

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represents the nonlinear coupling of the waves and is proportional to the corresponding components of the second-rank susceptibility tensor; \( \Delta k = 2k_w - k_{2\omega} \) is the difference between the wave numbers at the fundamental \((k_w)\) and second-harmonic \((k_{2\omega})\) frequencies, respectively. The group velocities of \( A_w \) and \( A_{2\omega} \) were assumed to be equal. This approximation, which allows us to ignore the secondary effects that accompany SHG [25], is valid for pulse durations down to 250 fs. This is true, for example, of a KTP crystal of length \( L = 1.5 \) mm with the normalised nonlinearity coefficient \( \gamma L/(\sigma_{12} T_{\text{cav}})^{1/2} = 1.5 \) when the parameters of the active medium correspond to \( \text{LiO}_{2} \cdot \text{Tl}^{3+} \) \((T_{\text{cav}} = 5 \text{ ns is the resonator cavity period}).\)

We postulated that \( \Delta kL = 0 \) applies during the forward trip through the modulator, i.e. the conversion to the second harmonic is efficient, and that after reflection from the dichroic mirror with the reflection coefficients \( R_w \) and \( R_{2\omega} = 1 \) at the fundamental and second harmonics, respectively, we have \( \Delta kL = \pi \), i.e. the second harmonic is converted back to the fundamental frequency. This amplitude modulator has discriminating properties practically throughout the full range of \( R_w \) and the dependence of its transmission \( T \) (i.e. of the ratio of the intensity of the fundamental-frequency radiation transmitted by the modulator to the intensity of the same radiation incident on the modulator) on the intensity of the incident fundamental-frequency radiation is similar to the familiar dependence of the transmission of a saturable absorber on the peak intensity of a pulse [24]. The small-signal transmission of the modulator is equal to \( R_w \); when \( R_w \) is increased, the degree of bleaching of the modulator (i.e. the difference between the transmission of the completely bleached modulator at high intensities of the incident field and the small-signal transmission) decreases.

Fig. 1 gives the dependence of the derivative of the modulator transmission with respect to the normalised intensity of the generated field \( U = \sigma_{12} T_{\text{cav}}/A_w^{\frac{1}{2}} \), representing the discriminating properties of the modulator, on the values of \( U \) and \( R_w \). We can see that at low \( U \) this derivative is maximal at \( R_w \approx 0.5 \), so that near this value of the reflection coefficient of the dichroic mirror we can expect effective positive discrimination of the fluctuation peaks of the field during the initial stage of lasing, so that the generation of ultrashort pulses is ensured. An increase in the intensity of the generated radiation enhances the effectiveness of the discrimination of the fluctuation peaks, governed by \( \partial T/\partial U \), but this is followed by a deterioration in the discrimination properties of the modulator, similar to the complete bleaching of a saturable absorber. The maximum discrimination of the modulator for the selected parameters of the nonlinear crystal and of the laser system occurs at a field intensity of \( \sim 20 \text{ MW cm}^{-2} \), which corresponds to typical intensities resulting in bleaching of saturable absorbers.

Fig. 2a shows (in the plane of variation of the normalised pump intensity, \( U_p = \sigma_{12} T_{\text{cav}}/P_p \), and of the reflection coefficient \( R_w \) of the dichroic mirror at the fundamental frequency) a region of effective mode locking where in the course of lasing a stable train of ultrashort pulses forms from the initial phase-amplitude noise radiation [15]. We can see that the increase in \( R_w \), which is accompanied by an increase in the transmission for a small-signal, reduces the mode-locking threshold. However, the width of the region governing the potential tuning of the system to the generation of ultrashort pulses is largest, as expected on the basis of Fig. 1, at \( R_w \approx 0.5 \), which corresponds to the strongest positive discrimination of the fluctuation peaks. These results are close to those obtained experimentally [21, 22].

An interesting property of the investigated modulator is the increase in the efficiency of SHG in the nonlinear crystal with an increase in the field intensity, so that the system generates trains of ultrashort pulses at the fundamental and second-harmonic frequencies. Within the limits of the effective mode-locking region (Fig. 2a) a reduction in \( R_w \).
is accompanied by an increase in the second-harmonic intensity at the modulator exit.

The modulator in question ensures effective mode locking over a wide range of parameters of the laser system. However, the necessary discrimination properties of SHG modulators can also be ensured without recourse to the conversion back from the second harmonic to the fundamental frequency, which should make it easier to satisfy the exact phase and group matching conditions in the femtosecond range of ultrashort pulse durations. The necessary effect can be achieved by the use of an additional resonator cavity or an antiresonant ring.

3. Modulators based on second-harmonic generation in an additional cavity or in an antiresonant ring

In the simplest SHG mode-locking system a laser is provided with an additional cavity containing a nonlinear crystal. This additional cavity, where the field is attenuated by SHG, is matched to the main cavity so that the field in the additional cavity is subtracted interferometrically from the field in the main cavity. As a result, the field losses in the main cavity decrease with an increase in the field intensity, which ensures positive discrimination of the fluctuation peaks. In a system of this kind the intracavity intensity is close to that typical for mode locking in a solid-state laser by a modulator based on SHG and a dichroic mirror, which has been built and tested \[2\]. This guarantees that the proposed modulator will be operational, because the physical mechanisms in the two modulators are the same.

Fig. 2b shows, in the plane of the parameters \( U_p \) and the reflection coefficient \( R \) of the mirror coupling the two resonators, a region of effective mode locking in a system of this kind, which is calculated on the basis of the fluctuation model \[15, 18\] when the fields in the main and additional cavities are coupled \[2\]. The intracavity intensity required for the discrimination of the fluctuation peaks corresponds to pump intensities close to the experimental values, as demonstrated in Fig. 2b (for the assumed laser system parameters the value \( U_p = 0.001 \) corresponds to the pump intensity \( I_p = 80 \text{ kW cm}^{-2} \)).

Effective mode locking requires an interferometric mismatch between the cavity lengths, so that the phase shifts experienced by the fields in these cavities are different:

\[
\phi = \pi \pm 0.2\pi.
\]

It is evident from Fig. 2b that effective mode locking is possible for \( R = 0.8 - 0.95 \) and the optimal value is \( R \approx 0.88 \).

A system with an additional cavity is capable of very effective mode locking at higher pump intensities \( U_p \) than a system with a dichroic-mirror moderator. However, the mode-locking threshold may be considerably reduced by a telescope, focusing the field on a nonlinear element inside the additional cavity. Another important shortcoming of systems with an additional cavity is the need to ensure long-term interferometrically exact matching of the cavity lengths.

Modulators based on an antiresonant ring are free of the last shortcoming. Fig. 3 shows a laser system for two types of such modulator. In the first type the cavity consists of a linear part — located ahead of a nontransmitting mirror \(8\) — and containing an active element \(1\) and a frequency filter \(2\) — and an antiresonant ring, formed by spherical mirrors \(9\) and \(10\), coupled to this part by a beam splitter \(3\) with a reflection coefficient \(R\). The ring splits the field into two counterpropagating fields \(A_1\) and \(A_2\), one of which satisfies the condition of efficient conversion to the second harmonic in a nonlinear crystal \(4\) placed between the two mirrors \(9\) and \(10\). Interferometric subtraction of the fields \(A_1\) and \(A_2\) in the beam splitter after a round trip through the resonant ring is ensured by introducing a nonreciprocal phase element, which induces a phase mismatch \(\phi\) between the counterpropagating fields. The initial transmission of such a modulator is controlled also by introducing linear losses into one of its arms, so that the transmission is loss-free \((S = 1)\) for the field \(A_1\) but is characterised by \(S < 1\) for the field \(A_2\). The nonreciprocal linear losses and the phase mismatch may be ensured by the same element based on the use of Faraday rotators and a polariser \[11\].

The transmission of such a modulator is

\[
T = PR^2(S^2\text{sech}^2\theta + 2S\text{sech}^2\theta\cos\phi + 1),
\]

where \(\theta = \text{LRA}(\phi)\) and \(P = 1 - R^2\) is the intensity transmission coefficient of the beam-splitting plate. Fig. 4a shows the dependence of the effectiveness of the discrimination of the fluctuation peaks, governed by the derivative \(\partial T/\partial U\), on the reflection coefficient \(R\) of the beam splitter and on the phase mismatch \(\phi\) between the fields counterpropagating in the ring. We can see that the positive derivative of the transmission with respect to the intensity, which ensures mode locking, is maximal for \(\phi = \pi\) and \(R \approx 0.7\). The initial small-signal transmission of the modulator increases with a reduction in \(S\) and is maximal at \(R = 0.5\).

Fig. 5 shows a region \((1)\) of effective mode locking for the modulator just described. In accordance with Fig. 4a, it is located in the range \(R = 0.4 - 0.8\). Replacing the nonlinear element in the waist between the spherical mirrors \(9\) and \(10\), where the intensity of the field is considerably higher, makes it possible to enhance significantly the SHG efficiency and thus lower the mode-locking threshold.

Let us consider the optimal nonreciprocal linear losses in the antiresonant ring. Calculations show that a reduction in the transmission \(S\) experienced by the field \(A_2\) increases the initial modulator transmission, but the derivative \(\partial T/\partial U\) is maximal at \(S = 0.5\). Hence, we can draw the conclusion that there is an optimal value of \(S\) that ensures the lowest mode-locking threshold, which depends both on...
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Figure 4. Effectiveness of discrimination in the case of a small signal reaching a modulator with SHG in the form of an antiresonant ring and a linear cavity when \( S = 0.2 \) (a) and a ring cavity (b) when \( 2d/\pi T_{\text{cav}} \) is 1, \( T_{\text{cav}} = 5 \text{ ns} \), plotted as a function of the reflection coefficient \( R \) of the beam-splitting plate and of the phase mismatch \( \phi \) between the fields counterpropagating in the ring.

Figure 5. Regions of effective mode locking for a modulator in the form of an antiresonant ring and a linear cavity when \( S = 0.2 \) (1) and a ring cavity (2). The other parameters are the same as in Fig. 2. The dashed curves inside region 2 identify the zone of existence of self-consistent solutions of the system of equations (3).

Figure 6. Curves representing the existence of self-consistent solutions of the system of equations (3) for a modulator in the form of an antiresonant ring and a linear cavity when \( S = 0.1 \) (1) or 0.2 (2). The other parameters are the same as in Fig. 2.

A comparison of Figs 5 and 6 demonstrates a good correspondence between the analytic solutions in the regions of effective mode locking, deduced from the fluctuation model. The parameters used in the analytic solutions represent the best balance between the factors that determine the generation of ultrashort pulses with the maximum stability and minimum duration close to \( t_{\text{f}} \).

If a single trip through the system produces only a small change in the field and if allowance is made for the delay \( \Delta t \) experienced by the field in a round trip along the cavity, the self-consistent solution of the system of equations (3) satisfies

\[
\left[ \frac{\partial}{\partial t} + \frac{1}{2} \ln T - A \frac{\partial}{\partial t} \right] A(t, z) = 0 ,
\]

where

\[
x(t) = x_0 \exp \left[ - \sigma_{32} \int_{-\infty}^{t} |A(t')|^2 \, dt' \right] ;
\]

\[
x_0 = x_m \frac{1 - \exp(-U_p)}{1 - \exp(-E - U_p)}
\]

is the gain ahead of the leading edge of an ultrashort pulse and \( E = \sigma_{32} \int_{-\infty}^{\infty} |V(t')|^2 \, dt' \) is proportional to the energy density in a pulse. It is assumed here that the pulse is localised in a time interval considerably less than the cavity period \( T_{\text{cav}} \).

Let the profile of the self-consistent field of an ultrashort pulse be Gaussian. Then expansion of the right-hand side of Eqn (4) in powers of \( t \) makes it possible to reduce Eqn (4) to a closed system of nonlinear algebraic equations which describe the parameters of ultrashort pulses as functions of the laser system parameters. Fig. 6 shows the normalised pump intensities and reflection coefficients of the beam-splitting plate for which there are physical solutions to these equations. The calculations show that the minimum permissible \( S \) at which there are approximate solutions of Eqn (4) in the form of a Gaussian pulse is 0.05. The lowest pumping rate \( U_p \) then corresponds to \( S = 0.1 \) (curve 1 in Fig. 6). An increase in the transmission \( S \) (curve 2) is accompanied by an increase in the pumping rate necessary to maintain the generation of ultrashort pulses.

A comparison of Figs 5 and 6 demonstrates a good correspondence between the analytic solutions in the regions of effective mode locking, deduced from the fluctuation model. The parameters used in the analytic solutions represent the best balance between the factors that determine the generation of ultrashort pulses with the maximum stability and minimum duration close to \( t_{\text{f}} \).

Systems with a dichroic mirror and a linear cavity containing an antiresonant ring do not allow the control of the initial modulator losses without a change in its discrimination properties, because \( R_m \) and \( S \) largely determine
both the initial losses and the discrimination properties. In this sense a ring laser system, shown schematically in Fig. 3 by dashed lines, provides more extensive opportunities. It represents a unidirectional ring cavity containing an antiresonant ring with interference properties that can be controlled by unbalancing the coupling to the main part of the cavity, so that there is no need for a component introducing nonlinear losses.

The transmission of a modulator based on an antiresonant ring in a ring cavity is

\[ T = P^2 R^4 \sec^2 \theta + 2PR^2 \sec \theta \cos \phi + P^2. \]  

The initial transmission of this modulator is high and effective discrimination of fluctuations is possible, as demonstrated by the derivative of the transmission (5) with respect to the intensity of the incident field under small-signal conditions (Fig. 4b). The value of \( \partial T/\partial U \) corresponding to the optimal values \( \phi = \pi \) and \( R = 0.3 \)–0.5 exceeds the corresponding value for a modulator based on an antiresonant ring in a linear cavity. Therefore, mode locking should be possible at much lower pumping rates. The corresponding region (2) of effective mode locking is shown in Fig. 5. We can see, as can be deduced from the behaviour of \( \partial T/\partial U \), that the minimum mode-locking threshold for \( R \approx 0.3 \) is much lower than that for a modulator in the form of an antiresonant ring in a linear cavity and of a laser with an additional cavity. This region lies within the range \( R = 0.2 \)–0.6, where \( \partial R/\partial U > 0 \). An increase in the reflection coefficient \( R \) of the beam-splitting plate first reduces the mode-locking threshold and widens the regions where this happens because of an increase in the 'strength' of discrimination of the fluctuations, but beyond \( R = 0.3 \) there is a steep rise in this threshold because of a reduction in the initial transmission and a change in the sign of \( \partial T/\partial U \).

It seemed of interest to analyse the feasibility of minimizing the durations of ultrashort pulses in such a modulator. The analytic model described above was used to find the parameters of the system corresponding to the generation of ultrashort pulses with maximum stability and minimum duration governed by \( t_e \). In the region in question (2 in Fig. 5) the zone corresponding to these parameters lies between the dashed curves. The minimum ultrashort pulse duration, amounting to \( 2t_e \), corresponds to \( R \approx 0.4 \) and \( U_p \approx 0.08 \).

4. Conclusions

We have analysed mode locking in continuously pumped solid-state lasers by four different modulators containing components capable of SHG. Three of these modulators are proposed for the first time. An analysis of the static properties of the modulators, the fluctuation model of continuous operation of solid-state lasers [15, 18], and the self-consistent solutions of an integro-differential equation describing the field transformation in such a laser system have yielded the parameters of a laser in which mode locking is characterised by the generation of a stable train of ultrashort pulses. Ways of increasing the effectiveness of such mode locking have been considered. It is shown that the minimum mode-locking threshold and the greatest width of the region of such locking, governing the selection of the system parameters ensuring the generation of ultrashort pulses, can be expected for a modulator with a dichroic mirror and also for one with an antiresonant ring in a ring cavity.

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