SELF-MODELOCKING OF CW SOLID-STATE LASERS BY NONLINEAR KERR POLARIZATION MODULATOR

V.L. Kalashnikov, V.P. Kalosha, V.P. Mikhailov, I.G. Poloyko, and M.I. Demchuk

Scientific-Research Institute for Applied Physics Problems,
Minsk State University,
220064 MINSK, Kurchatov Str., 7, USSR

ABSTRACT

Numerical simulation of self-modelocking of cw solid-state lasers with Kerr polarization modulator is developed. The limited ranges of laser and modulator parameters within which the laser generates stable train of ultra-short pulses are given.

Recently a new attractive modelocking technique has been demonstrated for cw Ti:sapphire laser generated ≈ 200 fs pulses.\textsuperscript{1,2} It utilized fast optical Kerr effect consisting in self-precession of field vibration ellipse proportional to intensity.\textsuperscript{3} The modulators based on this effect were proposed in Ref.4-6 and are analogous to noninertial saturable absorbers. Their locking parameters may be simply controlled by alignment of modulator polarization elements. As well as additive-pulse modelocking\textsuperscript{7,8}, the technique is applicable for self-starting of ultra-short pulse generation of cw lasers with various solid-state active media. Contrary to additive-pulse modelocking, it requires no interferometric stabilization systems for cavity adjustment. But the problem still remains to determine the laser parameters for which femtosecond pulse shaping self-starts. Here we present the results of numerical simulation of cw solid-state lasers with Kerr polarization modulator to make up for this deficiency. Enclosed regions of pump intensity and orientation angles of modulator analyzer where self-modelocking takes place are given depending on 'strength' of Kerr polarization effect and initial transmission of modulator.

Numerical model includes the investigation of temporal shaping of generation field \( V(t) \) by multiple transits through gain media, spectral filter of Fabri-Perot type and Kerr polarization modulator.

In the rate-equation approximation for cw pumping of four-level active media like Ti:sapphire the gain \( A \) is given by the equation\textsuperscript{13}

\[
\frac{dA}{dt} = \sigma_{14} (A_m - A)I_p - \sigma_{32} A |V|^2 - A/T_a,
\]

where \( \sigma_{14} \) and \( \sigma_{32} \) are the absorber and emission cross sections of laser medium, \( A_m \) is the maximum gain for full population inversion, \( I_p \) is the pump intensity, \( T_a \) is the gain relaxation time, \( t \) is local time in temporal window equal to cavity period \( T_{cav} \). The generation field is amplified by factor \( g = \exp(A - \Gamma) \), where \( \Gamma \) is the linear cavity losses.

The algorithm of spectral filter action was chosen to be the same as in Ref. 14-15. Fabry-Perot etalon as a spectral filter is characterized by transit time equal to the mesh time spacing \( \Delta t \) and by characteristic memory time \( t_f \) defined by reflectivity of etalon surfaces.

Assuming the linear polarization of laser field, the simplest design for Kerr polarization modulator is to be as follows: quarter-wave birefringent plate creating the elliptical polarization, Kerr medium sample changing the angle of inclination of vibrational ellipse and analyzer. Let \( \alpha \) be the angle between the polarization of input field and \( \lambda/4 \) plate main axis. Then the analysis\textsuperscript{3} gives the angle of self-precession of ellipse major axis

\[
\phi = p |V|^2 \sin 2\alpha
\]  

where \( p \) is Kerr polarization parameter proportional to the corresponding component of third-order nonlinear susceptibility and medium length. The estimation results in \( p / \sigma_{32} T_{cav} = 0.008 \) for 10 cm sample of carbon
bisulphate, Ti: sapphire emission cross-section and $T_{\text{cw}} = 10$ ns. If the analyzer plane makes an angle $\beta$ with $\lambda/4$ plate main axis, then the transmission of the modulator is

$$T = (\sin^2 \alpha \sin^2 \psi + \cos^2 \alpha \cos^2 \psi)$$

(2)

where $\psi = \beta - \phi$.

Eqs. (1) and (2) show no effect of intensity-dependent transmission of the modulator for linear ($\alpha = 0, \pi/2, \pi$) and circular ($\alpha = \pi/4, 3\pi/4$) polarization of the field in Kerr medium. Transmission (2) versus $\alpha$ and $\psi$ is displayed at Fig. 1. Some sections of this surface show the transmission which increases as a function of field intensity. At $p > 0$ the modulator possesses this property for $0 < \alpha < \pi/4$ and $0 < \beta < \pi/2$; $\pi/4 < \alpha < 3\pi/4$ and $\pi/2 < \beta < \pi$; etc. In contrast with the ordinary two-level absorber, owing to changes of $\alpha$ and $\beta$, the locking parameters of Kerr modulator, such as initial transmission and bleaching degree (i.e. difference between final and initial transmissions) may be independently chosen in wide ranges. As field intensity becomes large enough, so that $\phi > \beta$ or $\phi > \beta - \pi/2$ for corresponding surface sections (Fig. 1) the increasing of transmission is replaced by its decreasing. It appears that this darkening occurs for self-modelocking by Kerr polarization modulator.

The generation was initiated by spontaneous emission of gain medium. Gaussian noise with a lorentzian spectral profile characterized by coherent time $t_{\text{coh}}$ and a certain low noise level $N_{16} \leq 1\times10^{-7}$ was used. It should be emphasized that noise emission was added at each transit during all the laser generation time. Indefinite noise addition to laser field guarantees steady-state pulse for self-modelocked regime to be stable, independent of initial noise and defined by laser parameters only. Furthermore, it was verified that this noise addition causes considerable decreasing of self-modelocking parameter ranges and the rising of pump intensity threshold.

![Fig. 1. Transmission of Kerr polarization modulator.](image)

We have simulated the generation evolution of the laser with $\Delta = 1.5$, $T_{\text{m}} = 3.5\mu$s, $\Gamma = 0.2$, $\Delta t = t = t_{\text{m}} = 1$ ps, $N_{16} (\sigma, T_{\text{cw}})^{1/2} = 10^{-7}$ and different cavity period $T_{\text{cw}}$, normalized Kerr polarization parameters $p/\sigma_{32}^{\text{ph}}$, input modulator plate orientations $\alpha$ during 2000 transits to find out normalized pump intensities $\sigma_{32}^{\text{int}}$, $T_{\text{m}}$, and analyzer orientations $\beta$, for which stable trains of high-intensity ultrashort pulses are formed. An example of that self-modelocked generation dynamics is shown in Fig. 2.
fluctuations of the field because of the gain saturation\textsuperscript{17} and/or frequency-dependent processes involved\textsuperscript{16}. Passive modelocking of cw solid-state laser with ordinary saturable absorbers seems to be illustrated by the same picture. But it should be noted that the principal difference is the darkening of Kerr modulator at moments near steadystate pulse maxima. This negative feedback limits the pulse peak heights and stabilizes the laser generation.

Fig. 2. Evolution of ultra-short pulse self-modelocking for normalized intensity logarithm $U = \lg (\sigma_3 T_{\text{cav}} |V|^2)$, displayed at 2 transit intervals up to first 20 transits and at 20 transit intervals up to 740 transits. Laser parameters are $T_{\text{cav}} = 5$ ns, $\sigma_1 T_{\text{cav}} p = 0.4$, $p/\sigma_3 T_{\text{cav}} = 0.01$, $\alpha = \pi/12$, $\beta = 0.35\pi$ and others given in the text. Local time window which is only fifth part of cavity period near pulse peak is shown.

We have accepted that self-modelocking regime is accompanied with full concentration (99\%) of field energy near maximum peak continuously during a long period (10\% of the time of generation simulation). Self-modelocking ranges of pump intensity and analyzer angle $\beta$ for different Kerr polarization parameters and plate orientations were obtained according to this criterion and are presented on Fig.3.

As can be seen, the self-modelocking ranges are enclosed. Over the ranges several pulses are generated at cavity period, which are quickly transformed to their front satellites due to the pump action. They form essentially unstable generation trains. The lower boundaries of the ranges define the threshold pump intensities. Fig.3 shows that threshold pump depends on Kerr polarization parameter. The dimensions of self-modelocking ranges for given $p$ may be controlled efficiently by $\alpha$ and $\beta$ which define initial transmission and bleaching degree of the modulator. Increasing of $\beta$ within the limits of self-modelocking range causes a slight pump threshold increasing due to initial transmission decreasing. It leads also to increasing of pump intensity interval for which self-modelocking occurs, because of increasing of modulator bleaching degree. Comparing ranges 2 and 3 of Fig.3, it can be seen that the higher the bleaching degree, the quicker self-modelocking ranges broaden with $\beta$ along $I_p$ axis. Considerable rising of threshold takes place for $\beta \pi/2$ and the ranges become closed.
Our simulation showed the decreasing of temporal interval between the pulses in steady-state train, as pump intensity rises from threshold to upper boundary of the range of Fig.3. This interval becomes smaller than \((T_{cav} + t_f)\) because of primary amplification of pulse leading edge as pump increases. Over the ranges it results in satellite separation and unstable generation train. This outstripping of generation pulse may be compensated by choosing of greater filter characteristic time. Therefore the self-modelocking ranges of Fig.3 expand along the pump intensity axis for increasing of \(t_f\).

In summary, the numerical simulations of generation dynamics of cw solid-state lasers with Kerr polarization modulator have been developed. Shaping of stable ultra-short pulses from spontaneous noise emission performed by gain modulation, spectral filtering and intensity-dependent Kerr polarization effect has been demonstrated for limited ranges of laser parameters.

REFERENCES