Laser Physics Research Relevant to Laser-Electron X-Ray Generator

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Summary. A prototype of laser unit for Laser Electron X-Ray Generator is constructed on the basis of the optoelectronic control. The laser system in which an optoelectronic negative feedback is realized by means of a signal reflected from an intracavity Pockels cell polarizer is proposed and tested. The design provides flexible control over pulse train time structure.

1 Introduction

Laser produced plasma proved to be a convenient and flexible source of incoherent and coherent soft X-rays probably including water window in the near future. T³ and multiterawatt laser systems are being developed for efficient generation of hard X-rays [1]. However laser plasma X-ray sources are still uncompetitive with conventional X-ray tubes, synchrotrons and free electron lasers. Meanwhile a dramatic (several orders of magnitude) gap exists between X-ray tubes and accelerator based X-ray sources in respect of average power, brightness, sizes, cost, monochromaticity, tunability etc. The filling in of this gap would be beneficial for various scientific and commercial applications. In other words a new X-ray source that could bring together the compactness of X-ray tubes and X-ray beam manipulation ability of synchrotron radiation (SR) beamlines without the substantial rise of cost and loss of average power is highly desirable. The applications are biological and medical imaging, material structure and chemical analysis, protein crystallography, microscopy and microtomography for life sciences, medical diagnostics, industrial online X-ray inspection, security and custom control in ports and border terminals. A promising candidate to fill in the gap between conventional and SR sources is laser-electron X-ray generator (LEXG) based on Thomson scattering [2]. The idea to use Compton and Thomson scattering of laser radia-
tion by relativistic electrons to extend the output energy spectrum down to several tens keV [3] attracted last decade several research groups [4-12].

A project of LEXG developed jointly by Moscow State University and Institute of Quantum Radiophysics of P. N. Lebedev Physical Institute is aimed at the system containing pulsed synchrotron and a repetitive picosecond laser [11, 12]. Electron bunch is circulating in a storage ring and appears in the interaction chamber (IC) with the period 10-20 ns. Original laser beam time structure is a millisecond train of pulses separated by microsecond-scale intervals. Thanks to multiplication in optical circulator the period of laser signal is transformed from microsecond-scale interval into 10-20 ns inside the IC that provides the most efficient coupling of the laser and electron beams. Since the microsecond interval is far above a master oscillator’s resonator round-trip time $T_r$ (generally about 10 ns), one has to use pulse picking by means of an electrooptical modulator as it was made in [13] (see Fig. 1). A well-known method to obtain highly stable trains of picosecond pulses is to apply a system of feedback loops, which proved to be efficient in hundred microsecond range [14, 15]. Furthermore, feedbacks allow not only to stabilize the pulse amplitude, but also to obtain regular pulsations with controlled period far exceeding $T_r$ [16]. In this case a laser radiation looks like microtrains of picosecond pulses separated by microsecond intervals. It is important to note that such mode has an attrac-

Fig. 1. The near analogue of the LEXG laser system [13].
tive advantage. In fact, after single pulses at 0.5 MHz are picked from a train of pulses at 100 MHz, only 0.5% of average power is utilized. The mode of regular pulsations with 2-microsecond (0.5 MHz) period is more favorable, since it provides increase in intensity for the pulses picked in pulsation peaks.

2 Two Feedback Loops-Controlled Laser

To investigate the dynamics of a picosecond laser controlled by feedbacks we use the approach describing a mode-locked laser as an object with discontinuous control [16, 17]. In the simplest case of system with one negative feedback (NFB) loop delayed by a resonator round trip the control can be described by means of the so-called logistic mapping

$$x_{n+1} = rx_n (1-x_n)$$

(1)

where $x_n$ stands for a normalized energy at the $n$-th pass (a pass corresponds to a laser cavity round trip), $r$ is an overall gain including active medium gain and passive losses, and the term in brackets represents the one-pass delayed feedback loop action. The maximum acceptable gain for steady operation is $r_{\text{max}} = 3$ [16]. When $r$ exceeds the threshold value $r_{\text{max}}$, the logistic mapping demonstrates a well-known nonlinear dynamics [18].

Quite a different dynamics can be observed in a system controlled by two feedback loops (delayed by one and two round trips) described by the equation

$$x_{n+1} = rx_n \left(1 - \alpha x_n - x_{n-1}\right)$$

(2)

where $\alpha$ is relative feedback sensitivity. Its negative value denotes that feedback loop delayed by a resonator round trip is positive (PFB). The analysis shows that if $-1 < \alpha < 1$ a nonlinear dynamics displayed by (2)

![Fig. 2. Calculated log of pulsation period $T(r_{\text{max}})$ against relative feedback sensitivity: curves are in close agreement in the region of negative argument. The upper curve is an approximation.](image)
differs fundamentally from that of the logistic mapping (1): regular pulsation with period above three round-trips appears. The values of pulsation period $T(r_{\text{max}}(\alpha))$ at $r = r_{\text{max}}(\alpha)$ calculated by means of the mapping stationary point stability analysis and the approach based on differential equations (approximation) are presented in Fig. 2.

For negative $\alpha$ (i.e. positive and negative feedback combination control) at $r = r_{\text{max}}(\alpha)$ the pulsation is harmonic and the period can be expressed as

$$T(r_{\text{max}}(\alpha)) = \frac{2\pi}{\sqrt{\alpha + 1}}$$

(3)

Formula (3) implies that regular dynamics with large periods (tens and hundreds of round-trips) can be observed at $\alpha$ close to -1 (see Fig. 2).

3 Optoelectronic Feedback Designed for Pulsation Mode

The discussion above showed that pulsations with the period far exceeding a resonator round trip time are expected in a laser controlled by a combination of feedbacks where a negative feedback loop is delayed by one resonator round trip with regard to the positive one. With this aim in mind we designed a laser system in which an optoelectronic negative feedback is realized by means of a signal reflected from an intracavity Pockels cell polarizer.

Self-mode-locking in the negative feedback-controlled laser is a known technique for stable ultrashort pulses generation [19]. The laser mode-locked by a fast time-shifted negative optoelectronic feedback loop [20] is a very simple and reliable source of light pulses with about hundred pico-second duration. In such a laser the losses caused by an intracavity Pockels cell look like a periodic asymmetric "saw" with a long rise time and short tail. The tail is formed due to fast charge of the Pockels cell capacity by photocurrent generated in optoelectronic element under ultrashort light pulse. The long front is formed by slow discharge of intracavity cell capacity through the control system resistor. Stable self-mode-locking occurs due to time delay in feedback control system corresponding to light pulse passage through the Pockels cell at the moment of low intracavity losses. The discharge time should be [20, 21] about several cavity round trip time $T_r$. Optimal delay for short pulse generation is approximately one $T_r$. Usually the optical control signal is taken at the moment after passage of intracavity Pockels cell polarizer. The control proved to be efficient in laser output stabilization [16, 17].

The laser dynamics changes dramatically if the optoelectronic feedback is realized by means of a signal reflected from an intracavity Pockels cell.
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polarizer. The scheme of discontinuous control in the laser is shown in Fig. 3. When the laser pulse length varies slightly from pass to pass, the \( (n+1) \)-th pulse energy in the cavity \( E_{n+1} \) is related to \( E_n \) as

\[
E_{n+1} = E_n G^2 R P_n,
\]

where \( G \) is a gain in a round-trip and \( R \) is an output mirror reflectivity (see Fig. 3). Similarly to [16,17], we use the Pockels cell transmission \( P_n = P_0 (1 - B_n) \) where \( B_n \) is control signal, and \( P_0 \) is the initial Pockels cell transmission when feedback is off. In the proposed laser design \( B_n \) is the difference between incident light flux on the polarizer and transmitted flux.

\[
\begin{align*}
\text{Polarizer, P} & \quad \text{Gain medium, G} \\
\text{NFB} & \quad \text{Output mirror, R} \\
\left[ \begin{array}{c}
G^2 R E_{n+1} - E_n \\
\end{array} \right] & \quad \left[ \begin{array}{c}
\rightarrow G^2 R E_{n+1} \\
\end{array} \right] \\
\end{align*}
\]

**Fig. 3.** The scheme of discontinuous control in a laser with NFB: the control signal is taken from Pockels cell polarizer.

As a result for the recurrence relation we have

\[
E_{n+1} = E_n G^2 R P_0 \left( 1 - \left( E_{n-1} G^2 R - E_n \right) \right)
\]

(4)

Using \( r = G^2 R P_0 \) and \( E_n = x_n \frac{P_0}{r} \) one obtains

\[
x_{n+1} = x_n r \left( 1 - x_{n-1} + \frac{P_0}{r} x_n \right)
\]

(5)

Applying (3) and taking into account the Pockels cell transmission

\[
P(U) = \cos^2 \left( \frac{U}{U_{\lambda/2}} \frac{\pi}{2} \right)
\]

(6)

where \( U \) is a static bias voltage and \( U_{\lambda/2} \) is a cell half-wave voltage, we estimate the nonlinear dynamics development threshold gain \( r_{\text{max}}(U) \) and oscillation period \( T(U) \) in two limits.

When \( U \) is far less than \( U_{\lambda/2} \)

\[
T(U) = 2 \sqrt{\frac{2\pi U_{\lambda/2}}{U}}, \quad r_{\text{max}}(U) = 1 + \frac{\pi^2}{4} \left( \frac{U}{U_{\lambda/2}} \right)^2
\]

If \( U \to U_{\lambda/2} \), then \( T(U) \to 2\pi, \quad r_{\text{max}}(U) \to 2 \).
So the laser controlled by the optoelectronic NFB with the control signal taken from the Pockels cell a large period regular pulsation can be obtained. The period increases and the nonlinear dynamics development threshold decreases when the Pockels cell bias voltage $U$ decreases.

4 Laser Dynamics Simulation Results

To complete our demonstration of the laser, where the optoelectronic control signal is taken from the intracavity Pockels cell polarizer, however, we still have to show that the regime of pulsations can be reproduced qualitatively by extending the mapping (5) to take into account the laser output radiation fine time structure evolution as well as Pockels cell voltage variation at the time scale of $T_r$ depending on the feedback delay time, Pockels cell capacity discharge time, active medium gain, and the cell bias voltage $U_{st}$. We followed the same approach as in our previous works [16]. The goal is to investigate self mode-locking in pulsation regime with corresponding significant variation of control voltage and time-dependent Pockels cell transmission.

In the numerical simulation spontaneous emission noise was placed in the laser cavity and subsequently transformed by time-dependent transmission $P(t)$ of the Pockels cell. On the other hand $P(t)$ is calculated from the feedback signal proportional to the laser intensity $I(t)$ reflected from the intracavity polarizer.

The simulation proved that the discussed laser scheme allows not only to obtain stable mode-locking in quasi CW mode, but also to generate regular short pulses microtrains in pulsation regime with controlled period far exceeding $T_r$. When the laser parameters are optimal the

![Fig. 4. Simulated trains: $r = 1.03$ (a) and 1.09 (b).](image)
microtrain consists of tens single (at the cavity round trip time) short pulses. To show gain sensitivity of the microtrains envelope the trains at gain $r = 1.03$ and 1.09 are displayed in Fig. 4 (in both cases $U_{st} = 0.05 U_{s/2}$).

5 Experiment

The experiments were performed using a flash-lamp pumped Nd:YAG laser ($\varnothing 6.3 \times 60$ mm rod was used). A PC-controlled laser pumping based on the incomplete discharge of large capacity allowed us to vary pump duration up to 3.9 milliseconds. Laser cavity was made by flat wedge-shaped mirrors of 0.98 and 0.35 reflection coefficient. We introduced an intracavity mirror telescope 3:1 to enlarge a laser mode volume in the active media and thus to raise the laser output. Total cavity length was 150 cm. An iris aperture was used for mode selection. The Pockels cell was based on a

Fig. 5. Millisecond lamp pumped YAG-Nd laser designed for microsecond scale pulsations. AM active laser medium; M1, M2 cavity mirrors; P polarizer; IA iris aperture; MT – mirror telescope; DKDP Pockels cell electrooptical crystal; CC feedback control circuits.

Fig. 6. Traces of the lasing power (a) and pump lamp running (b) corresponding to discharge time 3.9 ms; time scale 0.5 ms/div.
multilayer polarizer (Brewster angle) and $8\times8\times11\,\text{mm}^3$ DKDP ($U_{\lambda/2} = 7.8\,\text{kV}$) crystal with antireflection faces placed close to the laser mirror. Static bias voltage $U_{st}$ applied to the Pockels cell was varied in a range $0\div2\,\text{kV}$. A high voltage silicon mesa-structure was used as a control element of the optoelectronic system. Discharge time of intracavity Pockels cell capacity was set to $20\,\text{ns} (2T_r)$. The control signal was taken from an intracavity Pockels cell polarizer (Fig. 5). A pin-diode and C8-14 storage (50 MHz) and digital TDS-3052 (5 GS/s, 500 MHz) oscilloscopes were used for the laser emission registration. Fine time structure of the laser light was investigated using streak-camera AGAT SF-3M (time resolution $<2\,\text{ps}$) synchronized with laser pulses with specially-made electronic delay system.

When kV range static bias voltage $U_{st}$ was applied to the Pockels cell stable mode-locking in quasi CW regime was observed. Setting the optimal diameter of intracavity iris aperture we obtained a picosecond pulse train of stable amplitude with total number of pulses up to 350000. The typical train shape and corresponding pumping pulse shape is shown in Fig. 6 a, b. By decreasing $U_{st}$ and fine DKPD crystal tuning we obtained regimes of regular pulsations with periods 0.5, 1, 1.3, and 2 microseconds. The ex-

![Fig. 7. The development of regular microsecond pulsations and a microtrain fine time structure in the mode-locked laser. Pulsation period is 200 round trips (2 microseconds). The dynamics is shown in three time scales: millisecond, microsecond and nanosecond.](image-url)
Experiments showed that despite of significant control voltage and time-dependent Pockels cell transmission variation in pulsation mode a single pulse was circulating in the laser cavity for the all regimes. An example of 2 microsecond period pulsation development is shown in Fig. 7.

Fig. 7. Example of 2 microsecond period pulsation development.

Millisecond time-scale oscilloscope traces (see Fig. 8) show that the peak pulsation power (feedback is on) is several times higher than a steady-state power level in free-running lasing (feedback is off, all other conditions being equal).

In conclusion the laser regime based on the combination of positive and negative feedbacks is obtained that provides efficient extraction of a single picosecond pulse with a microsecond period from mode-locked laser oscillator. We are grateful to N. A. Borisevich, V. G. Tunkin, V. A. Petukhov, Yu. S. Kasjanov, R. M. Feshchenko and A. M. Chekmarev for fruitful discussions. The work was partially supported by the Subprogram “Laser systems” of RAS and RFBR grant 05-02-17448a.

References