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Generation of Ultrashort Microwave Pulses in Passive Mode-Locked Electron Oscillators with Homogeneous and Inhomogeneous Line Broadening

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Introduction

In the laser physics the generation of ultrashort pulses (USP) via passive mode-locking [1] is broadly used. Gain media with homogeneous and inhomogeneous line broadening are applied [2]. The analog of homogeneous and inhomogeneous line broadening in microwave electronics is electron-wave interaction with beams having small or large initial energy spread. USP electron oscillators with passive mode locking with homogeneous line broadening were investigated in [3-4]. In this paper we will study peculiarities of the USP microwave oscillators with both homogeneous and inhomogeneous line broadening.

Model and basic equations

The schema of USP generators is presented in Fig. 1. It consists of an electronic amplifier, a nonlinear (saturable) absorber in the feedback circuit, and a partially transparent mirror for output of the signal.

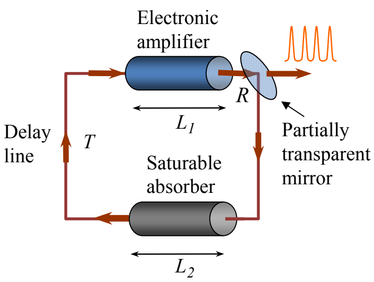

Fig. 1. Principal scheme of a USP oscillator with a saturable absorber in the feedback loop.

We will use a rather general model of the electronic amplifier with prevailing inertial particle bunching [5]. Under conditions of a relatively small energy change of particles $|1-\varepsilon/\overline{\varepsilon}|\ll 1$ (where $\varepsilon = mc^2\gamma$, γ is the relativistic factor, $\overline{\varepsilon}$ is an average value of electron energy in the initial distribution), the process of amplification can be described by the universal system of equations [5,6]

$$\frac{\partial a_n}{\partial Z}+\frac{\partial a_n}{\partial \tau}=J,\qquad \frac{\partial u}{\partial Z}=\mathrm{Re}\left(a_n e^{i\theta}\right),\quad \frac{\partial \theta}{\partial Z}=u. \tag{1}$$

The boundary condition for electrons is

$$u\big|_{Z=0}=u_0,\quad \theta\big|_{Z=0}=\theta_0\in[0;2\pi)\,. \tag{2}$$

We will suppose initial energy spread of electrons of the beam is normal

$$f_0(u_0)=\frac{1}{\sqrt{2\pi}\sigma}e^{-\frac{u_0^2}{2\sigma^2}} \tag{3}$$

where $\sigma=\mu C^{-1}\Delta\varepsilon/\overline{\varepsilon}$ is a parameter characterizing the electron energy spread, $J = 1/\pi\times \int_{-\infty}^{+\infty}\int_0^{2\pi} f_0(u_0)e^{-i\theta}d\theta_0 du_0$ is an amplitude of the high-frequency electron current, θ is an electron phase relative to a synchronous running wave, $u=\mu C^{-1}(1-\varepsilon/\overline{\varepsilon})$ is the normalized electron energy variations, $Z=C\omega z/c$, $\tau = C\omega(t-z/V_{\|0})\times (c/V_{gr}-c/V_{\|0})^{-1}$, $a_n=\chi\mu C^{-2}eA/mc$ is the normalized wave amplitude, n is the number of the field passages through the feedback loop, $L=C\omega l/c$ is the length of amplification region, $C=(eI_0\chi^2\mu/mc^3\overline{\gamma}N)^{1/3}$ is the parameter of amplification (Pierce' parameter), I_0 is the beam current, χ is the electron–wave coupling coefficient (see [6]), N is the operating mode norm, and $V_{gr}=d\omega/dh$ is the wave group velocity.

The signal passage in a feedback circuit with absorber is described by the equation

$$\frac{\partial a_n}{\partial Z}+\frac{\partial a_n}{\partial \tau}+\nu(a_n)\,a_n=0\,. \tag{4}$$

where the coefficient of attenuation ν for a saturable absorber can be specified as

$$\nu(a_n)=\frac{\nu_0}{1+\upsilon\,|a_n|^2}. \tag{5}$$

In accordance with the scheme shown in Fig. 1 boundary conditions can be presented in the form

$$a_{n,in}^{(2)}(\tau)=Ra_{n,out}^{(1)}(\tau),\qquad a_{n+1,in}^{(1)}(\tau)=b_{n,out}^{(2)}(\tau-T) \tag{6}$$

where index "1" and "2" corresponds to section of amplification and absorbing, respectively, R < 1 is the reflection coefficient, T is a delay time.

Electron efficiency of the oscillator is determined by the relationships

$$\eta=\frac{C}{\mu\left(1-\overline{\gamma}^{-1}\right)}\hat{\eta},\qquad \hat{\eta}=\frac{1}{2\pi}\int_0^{2\pi}u\left(Z=L_1\right)f_0(u_0)d\theta_0du_0. \tag{7}$$

Results of simulations

Results of simulations of USP generation via passive mode-locking with homogeneous (the initial electron energy spread is absent) and inhomogeneous line broadening (the initial electron energy spread $\sigma=2$) are presented in Fig. 2. For both cases one can

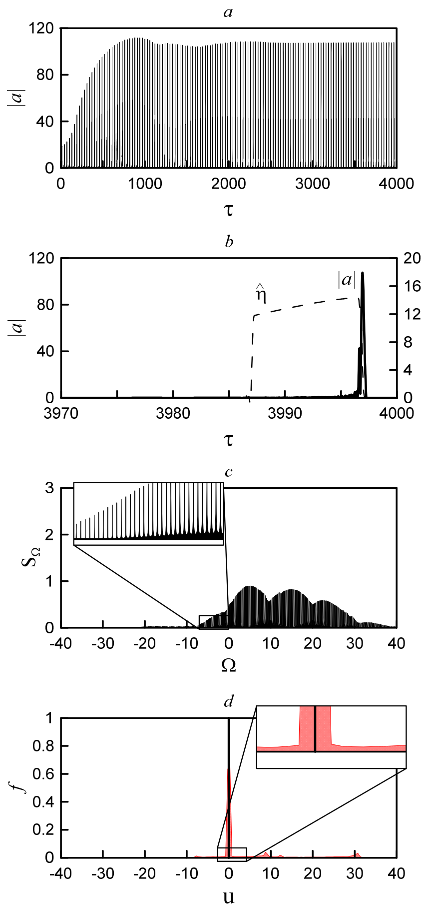

Fig. 2. Setting on a USP regime in the oscillator with homogeneous line broadening (L_1=10, R=0.9, L_2=5, ν_0=1.5, υ=0.6, T=20, $\sigma\to 0$): (a) time dependence of the field amplitude, (b) detailed profile of pulses and the instant electron efficiency in the extended time scale, (c) radiation spectrum, and (d) electron energy distribution function at the initial (black line) and final (red line) stages.

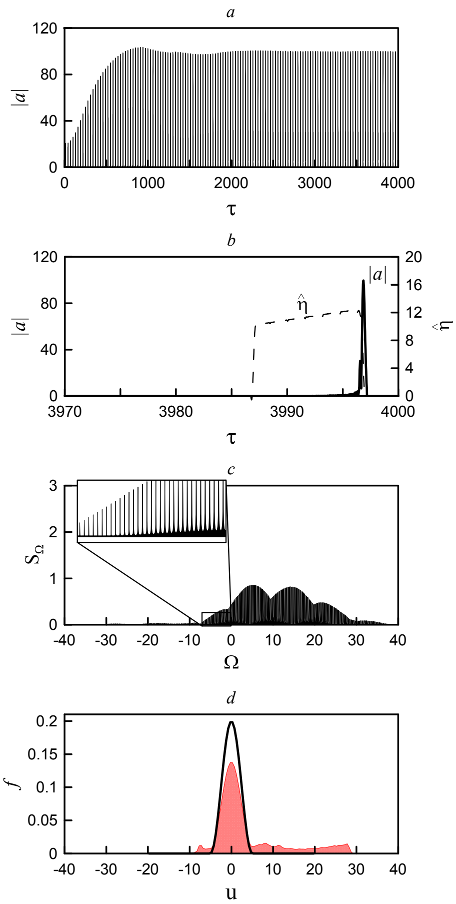

Fig. 3. Setting on a USP regime in the oscillator with inhomogeneous line broadening (σ = 2, other parameters are same as in Fig. 2): (a) time dependence of the field amplitude, (b) detailed profile of pulses and the instant electron efficiency in the extended time scale, (c) radiation spectrum, and (d) electron energy distribution function at the initial (black line) and final (red line) stages.

see that there is possibility of arrangement of mode locking regime accompanied by USP pulse production. For the same beam current, gain parameter and the length of amplification section the characteristic of generated pulses in regime with homogeneous and inhomogeneous line broadening is very closed. Nevertheless the peak amplitude of USP pulses is larger for the homogeneous line broadening.

Thus based on our analysis we can conclude that passive mode locking is an effective way to exploiting of powerful electron beams possessed by substantial energy spread (like high current relativistic electron beams) for generation of coherent radiation.

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