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Use of dynamical undulator mechanism to produce short wavelength radiation in volume FEL (VFEL)

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Abstract

VFEL lasing in a system with a dynamical undulator is described. In this system radiation of long wavelength creates the undulator for lasing at a shorter wavelength. Two diffraction gratings with different spatial periods form the VFEL resonator. The grating with longer period pumps the resonator with the long wavelength radiation to provide the necessary amplitude of the undulator field. The grating with the shorter period is used to select the mode for the short wavelength radiation. Lasing of such a system in the terahertz frequency range is discussed.

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Numerous applications can benefit from the development of powerful electromagnetic generators with frequency tuning in millimeter, submillimeter and terahertz wavelength range using low-relativistic electron beams. One of the ways to create such generators is to use VFEL principles. The main distinction of VFEL in comparison with the traditional FEL is the use of the non one-dimensional distributed feedback, which allows wide range tuning of frequency, decreases starting currents of generation and allows one to use a wide electron beam (or several beams) [1,2]. In the VFEL the generation evolves in a large volume that increases the electrical strength of the resonator (the electromagnetic power and electron beam are distributed over a greater volume). This peculiarity of the VFEL is essential for generation of power and super-power electromagnetic pulses. The mode discrimination in such an oversized system is carried out by multiwave dynamical diffraction [2]. Low relativistic electron beams in the undulator system can be used for radiation of short wavelength radiation, but it requires manufacturing of undulators with small period. For example, to obtain radiation with the wavelength 0.3–1 mm at the beam energy $E = 800$ KeV–1 MeV an undulator with the period ~ 0.3–1 cm is necessary. This is an extremely complicated problem. The use of a two-stage FEL with the dynamical wiggler generated by an electron beam [3] is a possible solution to the problem above. The dynamical wiggler can be created with the help of any radiation mechanism: Cherenkov, Smith-Purcell, quasi-Cherenkov [1], undulator. VFEL principles provide advantages of the two-stage generation scheme and, in particular, allow one to smoothly tune the period of dynamical wiggler by

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rotation of the diffraction grating. There is the possibility of smooth frequency tuning for both the pump wave and the signal wave either by variation of geometric parameters of the volume diffraction gratings or by their rotation. Moreover, the VFEL allows one to create the dynamical wiggler in a large volume, that is a great problem for a static wiggler. There are two stages in the generation scheme proposed above: (a) creation of the dynamical wiggler in a system with two-dimensional (three-dimensional) gratings (in other words, during this stage the electromagnetic field, which exists inside the VFEL resonator, is used to create the dynamical wiggler). Smooth variation of the orientation of the diffraction grating in the VFEL resonator provides means for a smooth change of the dynamical wiggler parameters; (b) radiation is generated by an electron beam interacting with the dynamic wiggler, which is created during the previous stage (stage a). Both stages evolve in the same volume.

The above idea of a two-stage tunable VFEL can be realized by different ways. Let us consider some examples (Fig. 1a–c). Fig. 1a displays the two stage device in which the dynamical wiggler is realized on the basis of a VFEL generator using the Smith-Purcell radiation mechanism. This generation scheme was considered in Ref. [4], when experimentally realized, first lasing of a VFEL was observed [5]. In this case only a part δl_x of an electron beam participates in the generation process during the first stage: $\delta l_x/l_x \sim \lambda_{\mathrm{w}}\beta\gamma/(4\pi l_x)$, here δl_x is the transverse size of the part of the electron beam participating in interaction, l_x is the transverse size of the electron beam, λ_{w} is the wavelength, $\beta = u/c$, u is the electron velocity, γ is the Lorentz factor. The resonator in Fig. 1a consists of two diffraction gratings [5]. The lower grating provides the Smith-Purcell generation mechanism. The period d_1 of this grating is determined by $d_1 \sim \beta\gamma^2\lambda_{\mathrm{w}}\cos\varphi$ (d_1 is the period of the Smith-Purcell grating, φ is the angle between the direction of the electron velocity and direction of the grating periodicity). The upper grating provides the distributed feedback [1,2] by multiwave dynamical diffraction. The conditions of dynamical diffraction $|\vec{k}_{\mathrm{w}}| \approx |\vec{k}_{\mathrm{w}} + \vec{\tau}_i|$ are fulfilled in this case ($\vec{\tau}_i$ are the reciprocal wave vectors of this grating). It should be noted that the period of the upper grating does not coincide with that of the lower one. Radiation accumulated in the resonator during the described first stage creates the dynamical wiggler. Beam electrons oscillate in this electromagnetic wiggler and radiate just as in a conventional FEL (this is not necessarily the same electron beam which participates the first stage. It can be another beam with higher energy). The field inside the resonator is a standing wave. Traveling waves, which form this standing wave actually are the pump waves. They are scattered by the electron beam according to the synchronism condition $\omega - (\vec{k}\vec{u}) \approx \omega_{\mathrm{w}} - (\vec{k}_{\mathrm{w}}\vec{u})$. The resulting wave has the wavelength $\lambda \sim (1-\beta)/(1+\beta)\lambda_{\mathrm{w}}$ (in the last estimation it is supposed that the wave vector of the pumping wave $\vec{k}_{\mathrm{w}}$ is antiparallel to the velocity

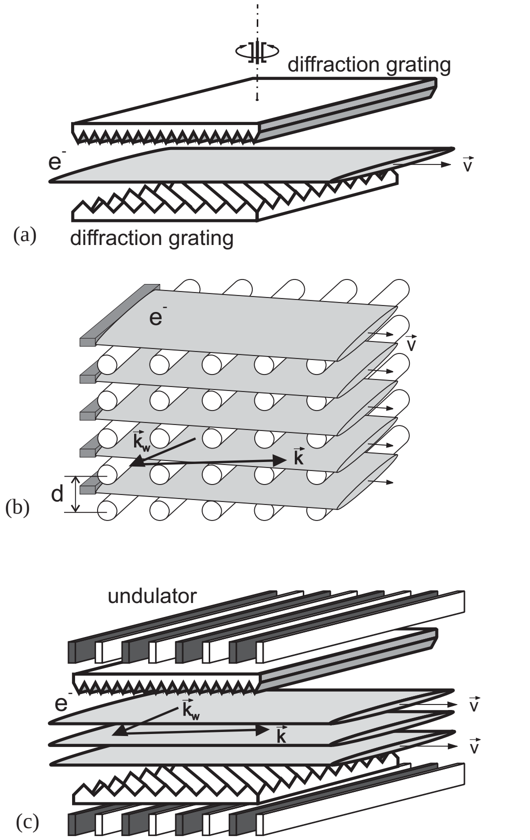

Fig. 1. The schemes of dynamic wiggler. Rotation of diffraction grating (schemes a and c) changes the period of dynamic wiggler.

and the wave vector $\vec{k}$ is parallel to it. For a relativistic beam this relation has the form $\lambda \sim \lambda_{\rm w}/(4\gamma^2)$. It should be emphasized that in this case there is one more possible way to create of the dynamical wiggler in the resonator shown in Fig. 1a. It is based on the excitation of a slow wave, which is diffracted by the lower grating (surface VFEL). The electron beam oscillates in this wiggler and radiates. In this case the upper grating forms the distributed feedback which provides VFEL lasing at shorter wavelength. The change of the radiated frequency is provided by the rotation of both the upper and lower gratings. Fig. 1b presents the variant of the volume diffraction grating which can provide the generation mechanism and distributed feedback simultaneously [1,2]. Let us note that in these examples the generation mechanism during the first stage is based on the slowing of the electromagnetic wave and only a part of the electron beam participates in the creation of the dynamical wiggler. The whole electron beam participates in the generation process during the second stage. The larger the fraction of the beam that does not participate in the first stage interaction, the more unperturbed electrons appear during the second stage and, therefore, they radiate more effectively. The dynamical wiggler in Fig. 1c uses the undulator radiation mechanism during the first stage. In this case the dynamical wiggler is formed during the first stage due to the interaction of the electron beam with a conventional magnetostatic undulator. The frequency of the pump wave is $\omega_{\rm w} \sim 2\pi\beta/d_{\rm u}(1-\beta\cos(\theta))$, where $d_{\rm u}$ is the period of magnetostatic undulator. During this stage the lower diffraction grating is used to provide the distributed feedback for the wave with frequency $\omega_{\rm w}$ and operation of the VFEL at this frequency. During the second stage, electrons oscillate in the field of this wave, which plays the role of the dynamical wiggler. As a result, during the second stage of the process the wave with a frequency $\omega \sim 4\gamma^2\omega_{\rm w}$ is generated and the distributed feedback is provided by the upper grating, the period of which corresponds the wave with the frequency ω. The rotation of diffraction gratings provide frequency tuning.

It is clear that the time $\tau_{\rm w}$ of the dynamical wiggler creation is a very important characteristic of the proposed system. This time is determined by $\tau_{\rm w} \sim Q/\omega_{\rm w}$, where $\omega_{\rm w}$ is the frequency of the pump wave. The Q factor of resonator for the frequency $\omega_{\rm w}$ should be sufficient to create a magnetic field amplitude of about 100 G–1 kG. It follows from the energy balance equation in the resonator, $(\omega_{\rm w}/Q)V(H_{\rm m}^2/8\pi) = W_0$, ($W_0$ is the power of pump wave formed by an electron beam) that $Q = (\omega_{\rm w}/W_0)V(H_{\rm m}^2/8\pi)$. V is the cavity volume and $H_{\rm m}$ is the amplitude of the magnetic field of the dynamical wiggler. It follows from the above that to create the magnetic field of about 100–1000 G, the time $\tau_{\rm w} \sim 10^{-10}$–$3\times10^{-9}$ s is necessary ($V = 30\ {\rm cm}^3$, $W \sim 30$ MW). As one can see this time is small enough that the wiggler can evolve while the electron beam passes through the system. When the pump field achieves the necessary magnitude stage (b) begins.

Dynamics of the signal electromagnetic wave and the electron beam in the system (volume diffraction grating + pump electromagnetic wave) in this case is described by equations [2]

$$\begin{aligned} &D_0E - \omega^2\chi_1E_1 - \omega^2\chi_2E_2 \\ &\quad - \omega^2\chi_3E_3 - \cdots = 0, \\ &\quad - \omega^2\chi_{-1}E + D_1E_1 - \omega^2\chi_{2-1}E_2 \\ &\quad - \omega^2\chi_{3-1}E_3 - \cdots = 0, \\ &\quad - \omega^2\chi_{-2}E - \omega^2\chi_{1-2}E_1 + D_2E_2 \\ &\quad - \omega^2\chi_{3-2}E_3 - \cdots = 0 \end{aligned} \tag{1}$$

In (1) $D_\alpha = k_\alpha^2c^2 - \omega^2\varepsilon + \chi_\alpha^{(b)}$, $\vec{k}_\alpha = \vec{k} + \vec{\tau}_\alpha$ is the vector of the diffracted wave, $\chi_\alpha^{(b)}$ is the part of the dielectric susceptibility corresponding to interaction of the electron beam with radiation

$$\chi_\alpha^{(b)} = \frac{q_\alpha^{(\rm w)}}{\{\omega - (\vec{k}_\alpha\vec{v}_{\rm w}) \mp (\omega_{\rm w} - (\vec{k}_{\rm w}\vec{v}))\}^2},$$

$$q_\alpha^{(\rm w)} = \frac{a_{\rm w}^2}{4\gamma^3}\frac{\omega_L^2}{(k_{\rm w}v)^2}\left\{\left[\frac{(\vec{u}\vec{e}_\alpha)}{c(k_{\rm w}v)}(\omega_{\rm w}\vec{u} - \vec{k}_{\rm w}c^2)(\vec{k}_\alpha - \vec{k}_{\rm w})\right.\right.$$

$$-\ (\vec{k}_\alpha \vec{e}_\mathrm{w})c\Bigg]\frac{(\vec{u}\vec{e}_\alpha)}{c}$$
$$-\ (\vec{k}_\mathrm{w}\vec{e}_\alpha)(\vec{u}\vec{e}_\mathrm{w}) - (\vec{e}_\alpha\vec{e}_\mathrm{w})(k_\mathrm{w}v)^2\Bigg\}^2$$
$$\times\ \{(\vec{k}_\alpha - \vec{k}_\mathrm{w})^2c^2 - (\omega - \omega_\mathrm{w})^2\}$$

$\vec{k}, \omega, \vec{e}$ and $\vec{k}_\mathrm{w}, \omega_\mathrm{w}, \vec{e}_\mathrm{w}$ are the wave vectors, frequencies and polarization vectors of both the signal and pump waves, respectively, $v = (c, \vec{u})$, $k_\mathrm{w} = (\omega_\mathrm{w}/c, \vec{k}_\mathrm{w})$, $a_\mathrm{w} = eH_\mathrm{w}/mc\omega_\mathrm{w}$. The dispersion equation corresponding to (1) has the following schematic form:

$$F^{(n)} = -\chi_\alpha^{(b)} F^{(n-1)}, \tag{2}$$

where the term $F^{(n)}$ in the left-hand side of (2) corresponds to the n-wave Bragg dynamical diffraction (equation $F^{(n)} = 0$ is the dispersion equation defining diffraction modes in n-wave case). The continuity of the current densities, charge densities and transverse components of the fields on the boundaries and dispersion equation (2) give the equation for the generation threshold [2]. From (1) we obtain that for n-fold degeneration point of the roots of the dispersion equation (when $n+1$ roots of the equation $D^{(m)} = 0$ at $m \geqslant n+1$ coincide) the equation for the generation threshold has the following form:

$$\frac{1}{\gamma^3}\left(\frac{\omega_L}{\omega}\right)^2 a_\mathrm{w}^2 k^3 L_*^3 = \frac{a_n}{(k|\chi|L_*)^{2n}} + b_n k \chi'' L_* \tag{3}$$

In Eq. (3) $k = \omega/c$, L_* is the length of interaction area of electron beam with electromagnetic radiation, χ'' is the imaginary part of the dielectric susceptibility, which describes absorption, a_n, b_n are the parameters depending on geometric parameters of the system (except L_*). The equality (3) has obvious physical meaning: the left-hand side of (3) contains the term describing generation of radiation by the electron beam, and the right-hand side includes those describing losses on the boundaries (the first term) and absorption losses (the second term) in the medium. One of the peculiarities of the VFEL with multi-wave distributed feedback is the possibility of a sharp decrease of losses at the boundaries (the first term in the right-hand side of (3) decreases with the increase of s due to condition $k|\chi|L_* \gg 1$ in conditions of dynamical diffraction). Let us express the synchronism condition for the above generation mechanism $\omega - \vec{k}\vec{v} = \Omega_\mathrm{w}$, where $\Omega_\mathrm{w} = \omega_\mathrm{w} - \vec{v}\vec{k}_\mathrm{w}$. Then, the frequency of the signal wave is equal to (if the pump wave is oncoming)

$$\omega = \frac{2\omega_\mathrm{w}(\vec{\tau}_1, \ldots, \vec{\tau}_n, \vec{n}_\mathrm{u}, S)(1 - \beta\cos(\Theta_\mathrm{w}))}{1 - \beta\cos(\Theta)} \tag{4}$$

In Eq. (4) the explicit dependence of the pump wave frequency on the geometry of the multi-wave diffraction $(\vec{\tau}_1, \ldots, \vec{\tau}_n)$ and the set of resonator parameters S is marked out (if a resonator is not oversized, then the dependence on S disappears). As smooth change of the VFEL geometry also varies the Q factor and, therefore, varies the generation efficiency. For example, the dependence of Q on the diffraction asymmetry factor $f = \gamma_0/\gamma_1$ is shown in the figure (γ_0, γ_1 are diffraction cosines [1]). It should be noted that the distributed feedback can be used for both the first and the second stages. To optimize the resulting radiation output the Q-factor can be controlled on both stages. Thus, for radiation angle $\Theta = 0$ $\omega \sim 4\gamma^2\omega_\mathrm{w}$, even the moderately relativistic electron beam ($E \sim 1$ MeV) gives a frequency multiplication ~ 35 times. If during the first stage the undulator mechanism is used (undulator period ~ 8 cm), then the wavelength of the pumping wave is $\lambda_\mathrm{w} \sim 1$ cm. Thus the signal wave is generated in the teraHertz range (Fig. 2).

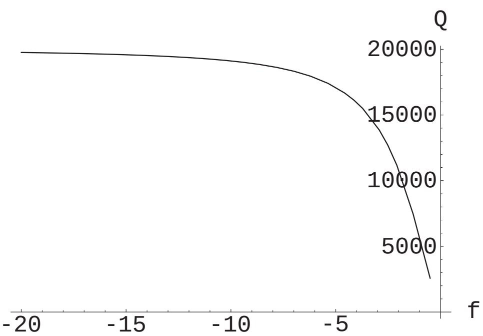

Fig. 2. Calculated dependence of Q factor on diffraction asymmetry factor f.

Thus, it is shown that: (1) the principles of VFEL can be used for creation of a dynamical wiggler with variable period in a large volume, (2) the two-stage scheme of generation can be used for lasing in the teraHertz frequency range by the use of low-relativistic beams and (3) the two-stage scheme of generation combined with the volume distributed feedback opens up the possibility of creating powerful generators with wide electron beams (or system of beams).

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