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Possibility for mode-locked operation of a femtosecond UV storage ring free-electron laser using a low-loss Fabry–Perot resonator

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ABSTRACT

A storage ring free-electron laser (SR-FEL) is inherently a self-mode-locked optical system. The gain broadening due to electron energy spread affects the small signal gain in order to determine the output coupling. Here, the dependence of the small signal gain, the optimum output coupling, and pulse duration on both electron energy spread and loss of a Fabry–Perot resonator in UV SR-FEL were investigated. It was shown that the output coupling strongly affects the mode-locked pulse duration and the present picosecond pulses can be shortened to femtosecond ones using a proper low-loss resonator.

1. Introduction

Today, there is increasing interest in the generation of intense, ultra short, tunable, coherent pulses in the short wavelength region [1–7]. Laser pulses of very short duration in the UV spectrum find applications in a large number of areas, such as analysis of transit-response of atoms and molecules, nonlinear optics in generation of harmonics, plasma remote sensing and range finding, induced plasma spectroscopy, time resolved UV photochemistry, diagnostic processes, high-speed photography, microlithography, space astronomy, and advanced research on laser induced fusion. Short pulse phenomena in atomic and molecular lasers have been studied extensively in the last decades. These include the nonlinear phenomena of self-spiking, as well as a wide range of mode-locking mechanisms and soliton formation. Mode-locked oscillation is known to be a very useful technique to get ultra short pulses in conventional laser oscillators [8–11]. The pulse duration obtained by this technique is roughly the inverse of the gain profile width. Excimer lasers are considered as the most powerful commercial UV sources [11,12] whereas the UV mode-locking of those lasers does not generate a train of short pulses smaller than a picosecond. Therefore, those are not very attractive short pulse generators, mainly because of their narrow bandwidth. Free electron lasers (FELs) potentially exhibit the ability to produce ultra short mode-locked pulses because the gain spectrum width is inherently very wide compared to that of most conventional lasers [13,14]. SR-FEL represents a very competitive technical approach to produce photons with these characteristics. After the first lasing of a SR-FEL in the visible range [15], the operation wavelength has been pushed to shorter values in various laboratories. These results are based on the progressive performance of particle accelerators and multilayer UV mirror technology to withstand the intense synchrotron radiation, which naturally damages the output coupler. An ultraviolet FEL oscillator has also been achieved using the VEPP ring at Novosobirsk [16].

A remarkable improvement has been obtained in recent decades at various laboratories [17–25] to produce laser lights as short as 190 nm, whose wavelength is similar to an ArF excimer laser. Present UV SR-FELs usually show typical mode-locked pulses of picosecond duration [14,18,26–28]. For instance, the time duration of a single pulse from a storage ring UV FEL (SRFEL) can be 15 ps FWHM [26]. At the recent years, a sub-picosecond coherent source in the VUV range on the Elettra storage ring FEL was reported [29,30]. The possibility of a mode-locked UV FEL operation at 190 nm was previously described and compared with existing ultra short pulse lasers with gaseous and solid-state gain media [31].

In this work, the optimum output coupling of resonator, pulse duration, and corresponding gain are investigated based on the undulator geometry using typical operational UV SR-FEL parameters for Elettra and Duke [32,33]. A self-mode-locked FEL as a transform limit of the gain profile offers the potential to generate short pulses in femtosecond duration, whereas presently the optical pulses of SR-FELs are several picoseconds FWHM. This will happen if the cavity loss can be decreased significantly.

2. Theory

Depending on current density and beam energy, FELs operate in one of four different regimes: Raman, low-gain Compton, high-gain

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collective, and strong-coupling high-gain regime. The Raman regime occurs at low energy and high current density. It is typical for devices that produce microwaves, whereas FELs aiming at the extreme ultraviolet, where high-reflectivity mirrors rarely exist, will necessarily have to operate in the high-gain collective regime. The existing Compton FELs cover the UV wavelength range to 200 nm. Electron storage rings are a promising source for FEL at short wavelengths. Here, the storage ring is chosen as a FEL accelerator having a slight inhomogeneous broadening component in a small signal gain regime, such as Compton or Raman low-gain regimes, where collective effects are not significant.

The gain of a FEL is related to the change of electron energy $\Delta\gamma$. In order to design a resonator for the FEL gain medium, small signal gain g_0 and saturation intensity I_s are taken into account. The line shape or normalized gain function $g(\nu)$ is a function of the detuning parameter, given by [34]

$$\nu = 2\pi N_u(\omega_0-\omega)/\omega_0 \tag{1}$$

where N_u represents the number of undulator periods and ω_0 is defined as

$$\omega_0 = 4\pi c\gamma^2/\lambda_u[1+K^2/2] \tag{2}$$

which denotes the resonant frequency, and λ_u is the undulator period. K is the undulator strength, $K=eB_0\lambda_u/2\pi m_0c^2$, where e is the electron charge magnitude, B_0 is the rms undulator field strength, and m_0 denotes the electron rest mass [34]. Then, the normalized gain in terms of the detuning parameter for low-gain, cold beam limit, is defined as

$$g(\nu) = \frac{2-2\cos\nu-\nu\sin\nu}{\nu^3} \tag{3}$$

which is antisymmetric in ν in the same way as the small signal gain function is equivalent to $G_0(\nu)=g_0g(\nu)$.

The main positive gain region is located at $\nu>0$, which corresponds to electrons traveling at velocities exceeding the synchronous value ($\nu=0$), where λ_0 is the resonant wavelength according to Eq. (2) such that $\lambda_0=\lambda_u(1+K^2/2)/2\gamma^2$. It should be noted that because ν depends on the optical frequency, the function $g(\nu)$ describes the gain frequency dependence. The small signal gain is directly proportional to the derivative of the spontaneous emission spectral profile. Fig. 1, which is relevant only for the low-gain limit within the small signal regime, depicts the spontaneous emission profile. It is a square sinc function in terms of the detuning parameter, where $\omega_0=2\pi c/\lambda_0$ and λ_0 is the emission wavelength at resonance. The derivative of the stimulated emission profile, which expresses the gain versus detuning parameter, is shown as well. As this profile becomes rather narrow, especially for a large number of undulator periods N_u, with the small proportionality constant, a high-quality electron beam is required having small energy spread and high current density.

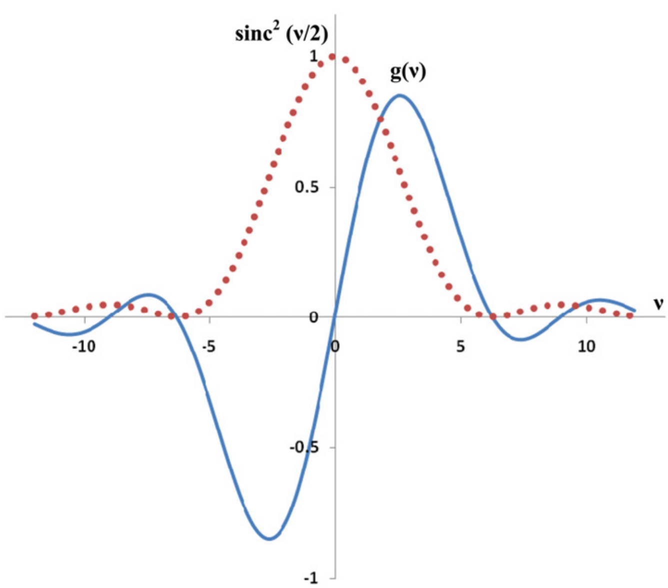

Fig. 1. Typical spontaneous emission profile (the dotted line) and gain profile of FEL versus detuning parameter.

The sources of energy spread cause further gain broadening homogeneously and inhomogeneously. In fact, this results in an increase of the number of longitudinal modes simultaneously. Therefore, there is an optimum design for an efficient mode-locked FEL resonator. A large number of longitudinal modes exist within the gain profile in the UV region, mainly due to long cavity length. As a result of the long cavity and the broad gain bandwidth, an FEL can oscillate in a large number of cavity modes, i.e., 10^6–10^7. In general, free-electron lasers have the potential ability to produce ultra short self-mode-locked pulses, because the width of the gain profile is inherently very wide compared to that of most conventional lasers. Conversely, small signal gain and saturation intensity strongly depend on the broadening effects.

The gain spectrum is characterized by a homogeneous width of the same order as the spontaneous emission. There are additional inhomogeneous broadening mechanisms related to the spread of individual electron parameters. The electron beam itself is a source of inhomogeneous broadening, which is related to the momentum spread of electrons and the finite transverse size of the electron beam distribution known as emittance. In the extreme UV, however, the demands on the transverse emittance of the beam are also very challenging. When the electrons enter the undulator, those located at different radii will experience different undulator fields. This causes an additional inhomogeneous broadening. The undulator inhomogeneity and the energy spread of electron from the accelerator are taken as the important inhomogeneous broadening sources accordingly. Homogenous broadening is related to slippage length which can be written as

$$(\Delta\omega/\omega)_{hom} = \frac{1}{2}N_u \tag{4}$$

and the inhomogeneous broadening is mainly due to: (i) emittance μ_x and μ_y, and (ii) energy spread μ_ε of the electron beam. The average relative energy spread is also called the natural rms energy spread $\sigma_{\varepsilon,0}$, such that [34]:

$$\mu_\varepsilon = 4N_u\sigma_{\varepsilon,0} \tag{5}$$

For Elettra $\sigma_{\varepsilon,0}$ is in the rage of 10^{-4}–10^{-3} denoting μ_ε to be from 0.1 up to 1 [28,35]. Total line broadening in a FEL is usually a combination of both homogenous and inhomogeneous effects, given by [34]

$$(\Delta\omega/\omega)_{Total} = (\Delta\omega/\omega)_{hom}\sqrt{1+\mu_\varepsilon^2+\mu_x^2+\mu_y^2} \tag{6}$$

where emittance and energy spread parameters induce a gain reduction, leading to the decrease in peak value of the spontaneous emission spectrum. It shall be noted that this approximation is valid to relatively small values of energy spread and emittance. In warm electron beams, the spectral broadening due to the emittance, if dominant, tends to be skewed towards the lower frequencies. This asymmetrical broadening effect is not included in Eq. (6), which is fine in this case.

In fact, there are several limitations to the performance of such a FEL storage ring. It has been shown that the emittance of the electron beam is one of the important factors of a storage ring for FEL operation. Particles in a storage ring perform synchrotron