

A MODE LOCKED UV-FEL

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Abstract

An appropriate resonator has been designed to generate femtosecond mode locked pulses in a UV FEL with the modulator performance based on the gain switching. The gain broadening due to electron energy spread affects on the gain parameters, small signal gain γ_0 and saturation intensity I_s , to determine the optimum output coupling as well.

INTRODUCTION

Today, there is an increasing interest in the generation of intense, tunable, coherent light in short wavelength region. Laser pulses of very short duration in UV/VUV spectrum, find applications in large number of areas, such as analysis of transit-response of atoms and molecules, non-linear optics in generation of harmonics, plasma remote sensing and range finding, induced plasma spectroscopy, time resolved UV photochemistry, diagnostic process, high speed photography, microlithography, space astronomy and the 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 [1-3].

The pulse duration obtained by this technique is roughly the inverse of the gain spectrum width. Using this technique, femtosecond pulses have been generated from Dye or Ti:Sa lasers, which possess the broad gain bandwidth among conventional lasers. Excimer lasers are taken into account as the most powerful commercial UV sources, whereas the UV mode-locking of those lasers do not generate a train of short pulses smaller than picosecond. Therefore, they do not resemble to be very attractive short pulse generators, mainly because of their narrow bandwidth. Among other UV lasers with mode-locking ability to generate tuneable ultra short pulses in VUV region, presently SHG Nd:YAG laser pumped THG/ FHG Ti:Al₂O₃ laser is considered as an attractive alternative.

Free-electron lasers (FELs) potentially have 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 [4]. In FEL oscillators, radiation burst and spikes have been observed in the nonlinear regime by several groups [5-10]. Although mode-locked FEL oscillators in microwave region have been formerly investigated both in theory and practice [11-12], however, a few papers are available to explain

FEL mode-locking phenomena for shorter wavelengths in far-infrared and infrared range of spectrum [13, 14].

In free-electron laser operating at the FIR and IR spectral regions, using a radio-frequency accelerator for the electron beam, when the electron pulse length can be of the same order as the slippage length or even shorter, the laser emits short pulses of multimode broad-band radiation [14].

On the other hand, Storage ring FEL represents a very competitive technical approach to produce photons with these characteristics. After the first lasing of a storage ring FEL (SRFEL) in visible [15], the operation wavelength has been pushed to shorter values in various laboratories. It is based on progressive performance of particle accelerators and multilayer UV mirrors technology as to withstand the intense synchrotron radiation which damages the output coupler. An ultraviolet FEL oscillator has also been achieved using the VEPP ring at Novosibirsk [16].

Radio-frequency linacs employ a series of cavities that contain radio-frequency (r.f.) electromagnetic fields to accelerate streams of electrons. Typically time structure for a laser pulse from a FEL is based on a pulse radio-frequency linear accelerator. The laser macropulse of microsecond duration consist of a train of short micropulses which are picosecond in length. The macropulses repeat at a repetition ratio limited by the accelerator in several tens of Hz. The micropulse repetition rate can be from several MHz to several GHz.

A remarkable improvement has been obtained in recent years at various laboratories [17-21] to produce laser lights as short as 190 nm, whose wavelength is similar to ArF excimer laser as an alternative powerful VUV coherent source. In this work, we investigate a mode-locked UV-FEL at 190 nm to compare it to existing ultra short pulse lasers with gaseous and solid-state gain media.

THEORY

Depending on the current density and beam energy, FELs operate in one of three different regimes: Raman, low-gain Compton and high-gain collective 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 the high reflectivity mirrors are non-existent, will necessary have to operate in the high-gain collective regime. The existing Compton FELs cover the UV wavelength range to 200 nm.

In order to design the resonator with the gain medium, the gain parameters, small signal gain γ_0 and saturation intensity I_s , are taken into account.

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The normalized gain function, $g(\nu)$, is a function of the parameter $\nu = 2\pi N_u (\omega_s - \omega) / \omega_s$, where N_u is the number of undulator periods, $\omega_s = 4\pi c \gamma^2 / [\lambda_u (1 + K^2/2)]$ is the resonant frequency and λ_u is the undulator period, and reads [22]:

$$g(\nu) = \frac{2 - 2\cos(\nu) - \nu\sin(\nu)}{\nu^3} \quad (1)$$

which is antisymmetric in ν .

The main positive gain region is located at $\nu > 0$ and corresponds to electrons traveling at velocities exceeding the synchronous value ($\nu = 0$). The condition $\nu = 0$ is equivalent to the synchronism condition: $\lambda_s = \lambda V_z / (c - V_z) = \lambda \beta_z / (1 - \beta_z)$ where $\beta_z = V_z / c$ and λ_s is the resonant wavelength $\lambda_s = \lambda_u (1 + K^2/2) / 2\gamma^2$ being K the undulator strength. V_z is the electron velocity in the undulator direction. It should be noted that since ν depends on the optical frequency, the function $g(\nu)$ describes the frequency dependence of the gain.

The small-signal gain is directly proportional to the derivative of the spontaneous emission spectral profile. Fig. (1) depicts the spontaneous emission profile which is a sinc function in terms of detuning parameters $(\lambda - \lambda_s) / \lambda_s$, where λ_s is the emission wavelength at resonance $\lambda_s = 2\pi c / \omega_s$. Fig. (2) represents the derivative of the profile as shown in Fig (1) to express the gain versus detuning parameter. As this profile becomes rather narrow, especially for a large number of undulator periods N_u , and the constant of proportionality is small, a high-quality electron beam with small energy spread and a corresponding high current density is required. In the extreme UV, however, the demands on the transverse emittance of the beam are also very challenging.

Fig. (2) illustrates the gain of FEL with the assumption of a negligible energy spread as shown in curve 1 Fig.(3), as well, though, the electron beam is not monoenergetic in practice. Therefore, curves 2, 3, 4 represent the broadened optical gain profile due to several electron energy spreads, as to that of curve 4 is four times of curve 2 and two times of curve 3 respectively.

The sources of energy spread cause further gain broadening homogeneously and inhomogeneously. The effect of energy spread in broadening can be corrected by the terms according to Fig. (3) which illustrates the small-signal gain variation versus detuning parameter for several electron energy spread. It obviously denotes that the gain peak becomes to decrease when the corresponding gain profiles is broadened.

Small-signal gain and saturation intensity strongly depend on the broadening effects. The gain spectrum is characterized by an homogeneous width of the same order of the spontaneous spectrum. 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

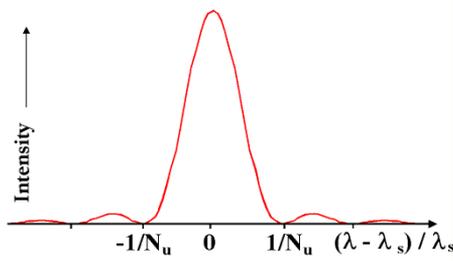


Figure 1: The spontaneous emission profile in terms of detuning parameter.

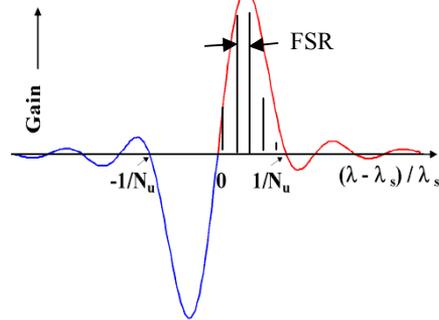


Figure 2: Gain versus detuning parameter.

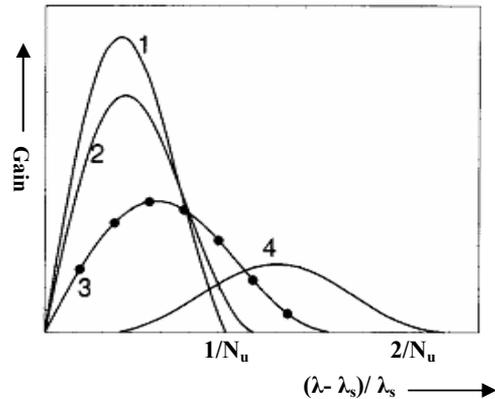


Figure 3: The effect of electron energy spread on the gain broadening of FEL. The curves 2, 3, 4 denote the relative electron energy spread [22].

to momentum spread of electrons, to the finite transverse size of the electron distribution. When the electrons enter the undulator, electrons located at different radii will experience different undulator fields and this will cause an additional inhomogeneous broadening. The undulator inhomogeneity and the energy spread of electron from the accelerator, as noted above, act to be the important inhomogeneous broadening sources accordingly. Due to the long cavity and the broad gain bandwidth, an FEL can oscillate in a very large number of cavity modes.

The homogeneous bandwidth usually exceeds the inhomogeneous one, and mode competition can cause a narrowing of the spectrum as in other lasers. The final width is determined by the quality factor of the cavity, the extending source of noise and by the duration of the pulse. For short pulses, the other effect dominates and the resulting spectrum width is to be transform limited in a FEL operating in the IR and FIR spectral regions, using a radio-frequency accelerator for the electron beam. A radio-frequency accelerator produces electrons in micropulses with a duration in the ps range. In a IR-FEL, based on such an accelerator, many modes are coupled due to the short pulse length.

The simulation of the coupling of pulses by an intracavity interferometric device, have shown that it is possible to induce coherence between independent pulses in an RF-linac based FEL. Apart from an ideal delay in the growth of the power and a gain reduction, due to absorption losses, the basic operation of the FEL is unaffected. The effect of an intracavity etalon on the spectral structure has shown that a low finesse etalon suffices to suppress most of the cavity modes and to concentrate the power in modes with a much larger frequency separation. Intracavity etalons or equivalent intraferometric elements are commonly used in conventional lasers to reduce the spectral bandwidth.

The application discussed here differs in that the free spectral range of etalon is much narrower than the full gain bandwidth and a sufficient number of active modes must remain present to compose the short pulses [14].

A MODEL OF MODE-LOCKED UV FEL

Let us assume, FEL oscillating on a homogeneous or inhomogeneous transition with many modes above threshold and lasing. A general equation describing the classical electromagnetic field at a particular point in space is $e_T(t) = \sum E_n \exp[j(\omega_0 + n\omega_c)t + \phi_n]$, E_n indicates the amplitude of n th mode, which is oscillating at the frequency $(\omega_0 + n\omega_c)$, where $\omega_c = 2\pi * \text{FSR}$. It is tempting to lock each mode to a common time origin and assign each phase to be zero. It leads to short pulse occurring at a repetitive rate.

We assume a Fabry-Perot cavity for the operation of FEL as a mode-locked laser. A characteristic parameter for a FEL is the slippage length $N_u \lambda_s$ where N_u is the number of undulator period and λ_s is the optical wavelength. It gives the difference between the distance traveled by an electron and by an optical wavefront, especially, in transit time for an electron through the undulator. The homogeneous gain bandwidth of a FEL is determined by the slippage length:

$$(\Delta\nu)_{\text{gain}} = \frac{c}{2N_u \lambda_s} \quad (2)$$

The Fourier transform limit for the bandwidth is given by $\Delta\nu = 1/\tau$ where τ is duration of light micropulse. For electron pulse long compared to the slippage length, the optical pulse length is almost equal to that of electron

pulse. For short electron pulse, the optical pulse length is on the order of the slippage length. In that case, the transform limit is as wide as the gain bandwidth so that no further narrowing is possible. Instead of mode competition, there is mode coupling and the FEL operates as synchronously pumped mode-locked laser.

For a resonator of length L , assuming the back mirror to be high reflective with $R_1 \sim 1$, then the output coupler reflectance R_2 is directly determined. Similarly, the corresponding equations are given as below:

$$\tau_{\text{RT}} = 2L/c \quad (3)$$

$$\text{FSR} = c/2L = 1/\tau_{\text{RT}} \quad (4)$$

where τ_{RT} , FSR and L denote the round trip time, free spectral range and length of the resonator respectively. The number of modes n is proportional to gain bandwidth which is written as below:

$$n = (\delta\nu)_{\text{gain}} / \text{FSR}. \quad (5)$$

The duration of mode locked pulses τ_p is related to τ_{RT} and n according to eq (6). For simplicity, assuming the constant mode amplitudes

$$\tau_p \sim 1/(\delta\nu)_{\text{gain}} = \tau_{\text{RT}} / n \quad (6)$$

however, for Gaussian distribution $\tau_p \sim 0.44/(\delta\nu)_{\text{gain}}$ accordingly.

A typical plane Fabry-Perot cavity scheme with length L for undulator parameters L_u and N_u , is shown in Fig 4. The gain parameters are related to undulator characteristics as well. The output temporal response of the resonator includes a train of ultrashort pulses with duration τ_p and period τ_{RT} between repetitive pulses.

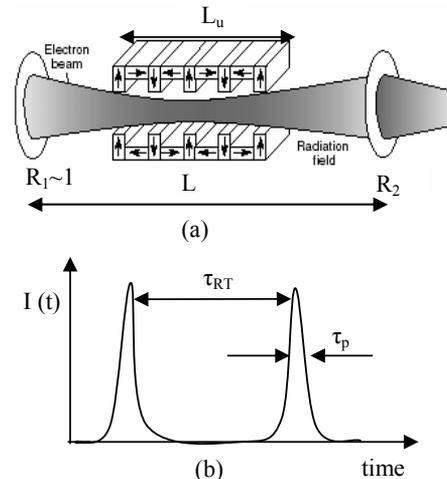


Figure 4: (a) A schematic Fabry-perot cavity
(b) Typical mode-locked output pulses,
 R_2 is output coupler.

According to laser amplification theory, for pulses whose shapes are sufficiently near the eigenfunction for

propagation in the homogeneous broadening, the change in the average temporal width τ of the pulse can be reasonably expected to be negligible, in such case, the effective saturation intensity is given by $I_s = \hbar\nu/2\sigma_{st}\tau$, where τ is the full width at half maximum (FWHM) of the probe pulse into gain medium, if $I \ll I_s$, then for low input intensities the gain increases and become equal to small-signal gain and for high intensities, the gain reduces to a saturated value with an intensity increment equivalent to $I_s \gamma_0 L$.

For a mode-locked laser, the small signal gain is also proportional to the population and stimulated cross-section which in turn depends on gain profile and the bandwidth. It indicates the frequency dependent γ_0 and I_s as well.

Fig.4 shows a typical Fabry-Perot with gain parameters γ_0 and I_s as to the axial mode width becomes relatively sharper. T_{opt} of the output coupler is given as below:

$$T_{opt}/A = (1 - A - T_{opt})[\gamma_0 L + \ln(1 - A - T_{opt})] / (A + T_{opt}) \quad (7)$$

where T_{opt} and A denote the optimum transmittance and the absorbance respectively for an optimum output coupler such that $T_{opt} = 1 - R_{opt} - A$.

The optimum design of mirrors in UV region of spectrum is achieved by the fabrication of pure multilayer coating of Aluminum oxide (or Hafnium oxide) on SiO_2 substrate. The gain switching for mode-locked laser requires to match the frequency of modulator to FSR (i.e. the spectral separation between the adjacent axial modes) of the resonator. In other words, the microbunching frequency should be tuned to FSR of Fabry-Perot resonator so as the repetition time of both electron micropulse and laser mode locked pulse become equal to the round trip time of the resonators τ_{RT} .

CONCLUSION

It is well understood, if the repetition time of the electron pulses is short compared to the round trip time of an optical pulse in the resonator cavity, then phase locking between successive optical pulses can be induced by an intracavity interferometer device. Moreover, for short electron pulse, the optical pulse length is in the order of the slippage length such that instead of mode competition, there is mode coupling and FEL operates as synchronously pumped mode-locked laser.

In UV region of spectrum, the slippage becomes smaller compared to that of IR region, therefore it is required to achieve shorter electron pulse length and broader gain bandwidth.

Moreover, for longer resonator cavity in UV-FEL, the resonator parameter FSR becomes relatively smaller for a given bandwidth to allow multimode operation with a great number of the active modes. In order to fulfill gain switching to generate a train of fs mode-locked pulses, the time repetition between successive pulses should be approximately equal to the round trip time of each pulse

in the resonator and the gain bandwidth broadens adequately.

We have proposed a preliminary design for the resonator based on the Fabry-Perot cavity to implement a UV self mode-locked FEL according to gain switching phenomena. It is shown that effects of gain broadening on the gain parameters strongly affects on the number of the axial modes within the bandwidth of the gain profile and the output coupling of the resonator consequently. The simulation have shown that the optimum mode locking occurs when the repetition time of the electron pulses is approximately equal to the round trip time of an optical pulse in the resonator cavity with the optimum output coupling, given by eq (7) for the definite gain parameters of a UV FEL.

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