CPC(HEP & NP), 2010, **34**(4): 512–515 **Chinese Physics C** Vol. 34, No. 4, Apr., 2010

Design study of an FEL oscillator with a waveguide*

LUO Feng(雒峰)[1,2;1)] BEI Hua(卑华)[1,2] DAI Zhi-Min(戴志敏)[1]

[1] Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai 201800, China
[2] Graduate University of Chinese Academy of Sciences, Beijing 100049, China

Abstract We present a design study of a free electron laser (FEL) oscillator for high power THz source experiments on the basis of the Shanghai femtosecond accelerator device. A circular groove guide is used as a new interaction structure. Plane metal meshes are used as upstream and downstream mirrors of the resonator. The general design parameters are presented. We analyzed the spontaneous emission and stimulated emission in the oscillator using these parameters.

Key words free electron laser, circular groove guide, metal mesh, coherent radiation

PACS 41.60.Cr, 41.75.Ht

1 Introduction

In a free electron laser (FEL) oscillator the radiation emitted by relativistic electrons traveling through a periodic magnetic structure, the so-called undulator, is captured in an optical cavity and amplified on successive passes through the undulator. Compared to the conversional FEL, new issues arise in a long wavelength FEL due to the short electron pulse and the radiation diffraction loss. When the electron bunch is shorter than the radiation wavelength, individual emitted fields would add up in phase, resulting in the coherent radiation [1].

An effective way to reduce the diffraction loss for a long wavelength FEL is to adopt a waveguide. This is usually seen in far-infrared FEL devices. The small cross section of the fundamental mode results in a good transverse coupling for the field with the electron beam. Also in a waveguide the group velocity of the field is tunable and therefore makes it possible to reduce the slippage [2–4] (that is, the lack of overlapping between the wave packet and the electron bunch due to their different velocities). Several FEL operations with waveguides [5, 6] have been reported. For the submillimeter wave, we choose the low loss structure: circular groove guide [7].

On the other hand, in order to simplify the facility, we adopt a kind of electron transparent mirror (ETM) [8, 9], a metal mesh as the reflecting mirror. Application of a metal mesh in an FEL can save space that is needed to inject and extract the electron beam in a conventional FEL facility. A short cavity also means a reduced waveguide loss.

In this paper, we report on a design study of an FEL oscillator for a high-power THz source. There are a variety of interesting effects to be studied in the THz wave band in solid-state physics and molecular science [10], since many materials have distinct absorptive and dispersive properties in this spectral range.

2 Circular groove guide

A circular groove guide was first proposed by Prof. Yang Hongsheng [11]. It is a kind of low loss, high power handling, low dispersion and single mode transmission medium in the millimeter and submillimeter wave ranges. Fig. 1 shows the cross section of the circular groove guide. The circular groove region is marked with A. The diameter of the groove is $2a$. The two side regions are marked by B. The parallel plates' separation is $2c$. The overall transverse width is $2h$.

The properties of the fundamental mode in the guide have been described in detail in Ref. [7]. The electric field component in the central part of the

---

Received 10 June 2009

* Supported by Major State Basic Research Development Program of China (2002CB713600)

1) E-mail: luofeng@sinap.ac.cn

guide is mainly parallel to the plates. And the field in region B is exponentially evanescent. Here we only give the numerical results of its cutoff wavelength λ_c, related to the proper choice of the waveguide dimensions in order to operate the FEL oscillator at near zero slippage condition [5]. Fig. 2 shows the variation of the normalized cutoff wavelength with c/a in 1st order, 2nd order and 3rd order approximation [7].

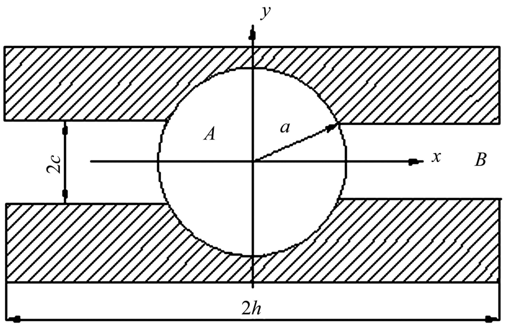

Fig. 1. Cross section of the circular groove guide.

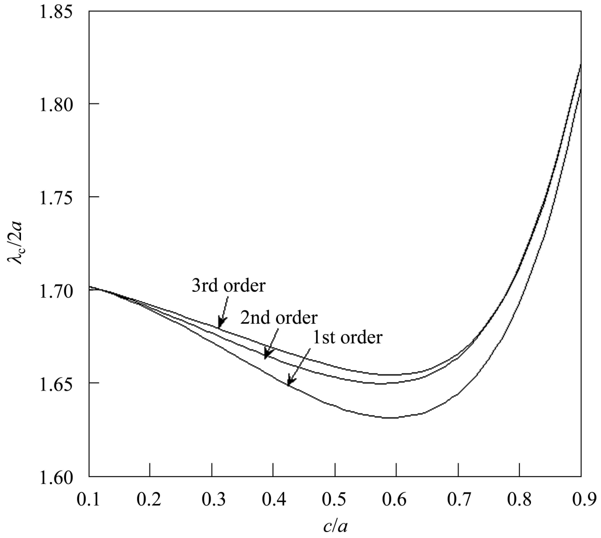

Fig. 2. Variation of $\lambda_c/2a$ with c/a in various approximations.

3 Cavity mirror: metal mesh

A metal mesh is characterized by a grid constant g, a strip width $2a$, and a thickness t. When the metal mesh is used as an input mirror for the FEL oscillator, one should pay attention to its influence on the electron bunch's quality. If it is used as an output mirror, one should particularly consider its optical properties. If the wavelength λ is larger than g, then only the zero-order wave is transmitted, which will improve the angular distribution of the output light wave. We suppose that $g < \lambda$ and normal incidence in the following part of this paper.

Generally the optical properties of a metal mesh can be described by a simple transmission line equivalent circuit. This has been extensively discussed in the literature. In Fig. 3, we plot the reflectivity R at $\lambda = 700$ μm as a function of the ratio g/λ for different a_{eff}/g values using the equations of reference [12]. Here a_{eff} is the effective strip width considering the finite thickness of the metal.

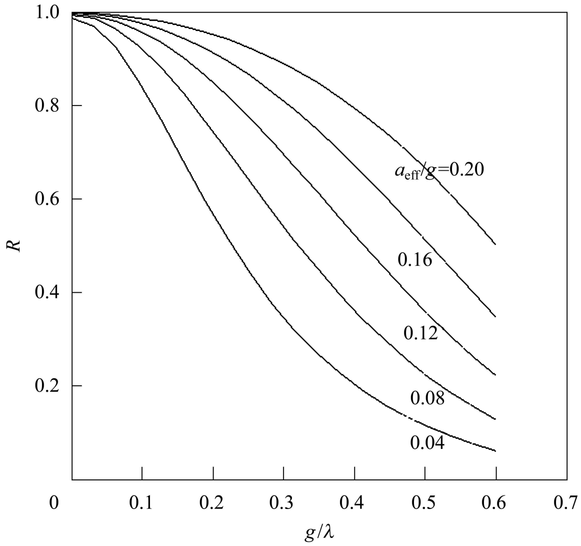

Fig. 3. Reflectivity versus g/λ for different values of the ratio a_{eff}/g.

4 Features of spontaneous emission in a waveguide FEL

In a waveguide FEL there are usually two resonant frequencies. The emitted optical pulse comprises two wave packets: a high frequency one, anticipating the electron bunch, and a low frequency one, following behind. A particular condition is found when there is only one resonant frequency. This is usually called "zero slippage" condition in which the group velocity of the wave packet equals the beam velocity. However, in the strict zero slip condition, the resonant frequency is quite sensitive to a change of the electron beam energy and the dimensions of the guide [2]. This may introduce instability. So in practice we adopt a near zero slip operation by a proper choice of the operation parameters.

The simulation parameters are listed in Table 1. The corresponding resonant electron energy in strict zero slip condition is about 23.8 MeV. The electron bunch pulsewidth is much shorter than our designed radiation wavelength. Assuming a Gaussian electron beam bunch distribution $f(t) = \exp(-t^2/t_b^2)/(\sqrt{\pi}t_b)$, ($t_b = 250$ fs), we plot the single pass emission spectral energy emitted on axis for a single electron bunch in Fig. 4, based on Gover's superradiant theory [13, 14]. The corresponding time dependent radiation field of the wave packet is also presented. From the picture we see that the two resonant peaks overlap (Fig. 4(a)). For the coherent interference of a larger number of individual radiations an optical pulse is formed (Fig. 4(b)).

Table 1. Simulation parameters.

electron beam	
beam energy	25 MeV
micro-bunch peak current	200 A
radio frequency	2.856 GHz
micro-bunch duration (FWHM)	250 fs
undulator	
period	10 cm
number of periods	5
peak magnetic field	0.59 T
circular groove guide	
radius of central groove	2.6 mm
overall width	20 mm
c/a	0.65

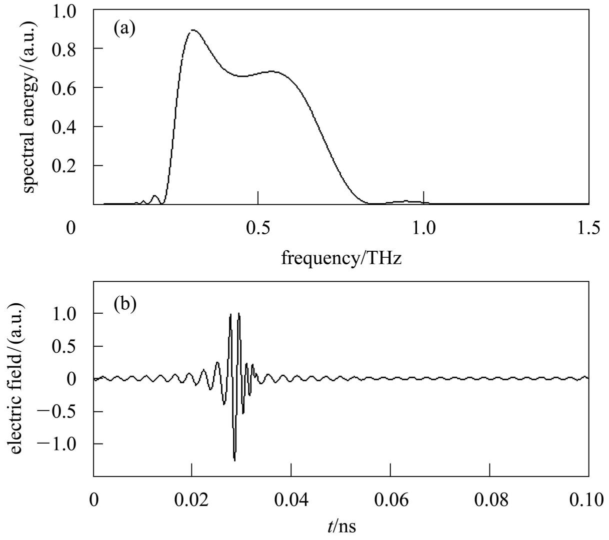

Fig. 4. Energy spectrum (a) and time dependence (b) of the radiation field.

5 Simulation of an FEL oscillator

Before discussing the simulation, we have to say a few words on the synchronization issue. From Fig. 4, one notices that at near zero slippage operation we can get a broad-band radiation spectrum. Due to the dispersion of the waveguide, there must be a frequency between the two resonant frequencies, whose group velocity equals to the electron velocity. The radiation at this frequency will be consistently enhanced in the oscillating process. And consequently, the output emission must be centralized around this synchronous frequency. This has been verified by experiment [6]. On the other hand, the FEL oscillators are multi-pass devices. The resonator length must be set to synchronize the electron bunches and the wave packet of the radiation:

$$L=\frac{1}{2}v_{\rm g}nT_{\rm rf}\ .$$

Where L is the resonator length, $v_{\rm g}$ is the group velocity of the wave, n is the number of RF cycles per round trip of the radiation in the resonator, and $T_{\rm rf}$ is the period of the RF. Assume v_z is the longitudinal velocity of the electron beam. Using the condition $v_{\rm g}=v_z$ at the particular group-synchronous frequency mentioned above and the parameters in Table 1, we get a resonator length L = 62.81 cm for n = 12. This length is some distance longer than the length of the undulator, leaving enough space to mount the reflectors (metal meshes). The resonant oscillating frequency is about 0.423 THz (709 μm). This wavelength is long enough to achieve a coherent emission from the femtosecond electron bunches. The waveguide loss is calculated to be about 5.7% at this wavelength per single pass, using the sixth order approximation of the field distribution [15].

With a view to being commercially available, we choose the input mirror's dimensions as follows: $g=50.8$ μm, $2a=11.4$ μm, and $t=4$ μm, which gives an area transparency of 60% and its effect on the e-beam is not significant according to reference [9]. The reflectivity of this copper mesh is about 98.8% at λ = 709 μm. As for the output mirror, the dimensions are g = 76.3 μm, $2a$ = 12.45 μm, and $t=4$ μm. The transmissivity of this mesh is about 4.5% at $\lambda=709$ μm.

To investigate the oscillation process in the resonator, the interaction between the electron beam and electromagnetic field has been analyzed by solving the well known FEL pendulum equation and the energy conservation relation under the following hypotheses:

1) the cross section of the electron beam is negligible compared to the waveguide dimensions, ideal electron beam with no energy spread, on axis injection.

2) the electron beam interacts only with the dominant mode in the waveguide.

3) the electrons are tightly bunched. All electrons oscillate at the same phase. The initial phase of the electrons relative to the wave is assumed to be

zero. The initial detuning energy of the electrons is 25.4 MeV.

Figure 5 displays the evolution of the intra-cavity peak power at the synchronous frequency in consecutive round-trips starting from noise. In the simulation, a rough self-consistent condition has been used by updating the waveguide field at every round-trip. The number of round trips required for saturation is about 31. So the macropulse width of 2 μs is long enough to saturate the radiation.

In conclusion, we used a circular groove guide as the new interaction structure and copper meshes as cavity mirrors in an FEL oscillator. We have studied the coherent spontaneous emission and the oscillation buildup process in a waveguide mode FEL in the near “zero slippage” operation. We calculated the oscillation at the frequency where the group velocity of the radiation was equal to the electron longitudinal velocity. Further works are needed for more accurate analysis of the emission process in a short pulse FEL with a waveguide.

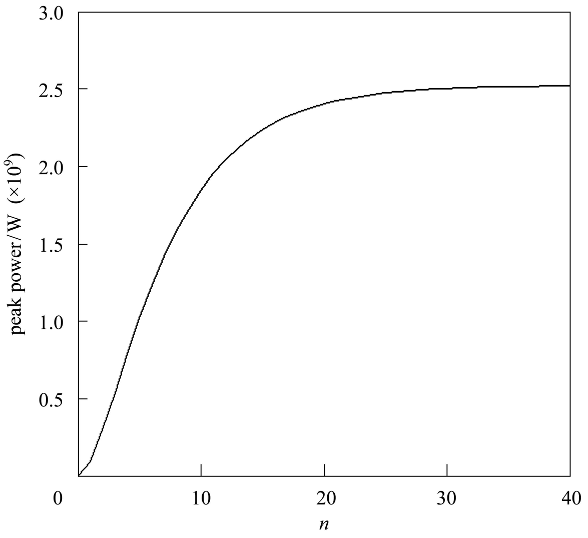

Fig. 5. Peak power as a function of the round-trip numbers.

References

1 Doria A, Bartolini R et al. IEEE Journal of Quantum Electronics, 1993, **29**: 1428

2 Ride S K, Pantell R H, Feinstein. Appl. Phys. Lett., 1990, **57**: 1283

3 Doria A, Gallerano G P, Renieri A. Opt. Commun., 1991, **80**: 417

4 Bartolini R, Doria A, Gallerano G P et al. Nucl. Instrum. Methods: Phys. Res., Sect. A, 1991, **304**: 417

5 Ciocci F, Bartolini R, Doria A et al. Phys. Rev. Lett., 1993, **70**: 928

6 Asakawa M, Sakamoto N, Inoue N et al. Apll. Phys. Lett., 1994, **64**: 1601

7 YANG H S, MA J L, LU Z Z. IEEE Trans. Microwave Theory Tech., 1995, **43**: 324

8 McAdoo J M, Granatsteim V L. Optics Letters, 1983, **8**: 316

9 Dipace A, Doria A, Gallerano G P et al. IEEE J. Quantum Electron., 1991, **27**: 2629

10 Carr G L, Martin M C, McKinney W R et al. Nature, 2002, **420**: 153

11 YANG H S, MA J L, LU Z Z. A New Type of Groove Guide. 2nd Int. Sump. Recent. Advances in Microwave Tech., Beijing, 1989: 239

12 Ulrich R, Bridges T J, Pollak M A. Appl. Opt., 1970, **9**: 2511

13 Gover A. Phys. Rev. ST. Accel. Beam, 2005, **8**: 030701

14 Gover A, Dyunim E et al. Phys. Rev. ST. Accel. Beam, 2005, **8**: 030702

15 YANG H S, LIU Y. IEEE Microwave and Wireless Components Letters, 2002, **12**: 57