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WAVEGUIDE FEL OSCILLATOR SIMULATION WITH TOROIDAL MIRROR

Yuanfang Xu*, Zhouyu Zhao, Heting Li, Qika Jia,
University of Science and Technology of China, Hefei, China

Abstract

FEL oscillator is the main working mode to produce infrared and THz radiation. However, in the long wavelength range, the waveguide is essential to suppress the diffraction losses. We have developed a method to study this effect by wGenesis that is modified with Genesis in combination with OPC code. However, this method is limited by the optical elements given in OPC. In this paper, we tried to give a more general optical element case based on the ABCD matrix. Then the simulation based on FELiChEM parameter is done to reduce the truncation loss at the waveguide port by choosing proper toroidal curvature radius. The results show that output power can be increased about 6.4 times than spherical mirror.

INTRODUCTION

In the long wavelength regime, such as far-infrared & THz, a larger transverse optical mode would bring high diffraction losses. A waveguide inserted inside the undulator can be used to reduce diffraction losses [1]. This waveguide can also introduce a better filling factor that means a larger gain. However, adding a waveguide may also lead to several disadvantages, such as lengthening of optical pulses, shifting of radiation wavelength, alteration of optimal cavity detuning, spectral gap and so on [2, 3]. These are mainly due to the reason that optical field longitudinal and transverse mode is distorted by the waveguide.

FELiChEM is a FEL oscillator facility in Hefei, China. It is now under commissioning to offer 2 ∼ 200 μm range wavelength [4]. For this large wavelength range, the waveguide is also applied. The experiment results of MIR and FIR range have shown obviously the spectral gap phenomenon causing by waveguide. To study the waveguide effect, We have developed a simulation method based on the modification of Genesis code [5]. The simulation results agree well with experiment.

The experimental and simulation result show that the laser power is quite low in long wavelength range. It is mainly caused by the truncation loss at the waveguide port. Then special mirror are proposed to match the optical spot size with waveguide, like toroidal mirror and cylindrical mirror [6, 7]. Therefore in this paper, we developed a method to describe the waveguide effect with special cavity mirror cases. Then the FELiChEM laser power at long wavelength is increased with proper parameter chosen.

* xyf1224@ustc.edu.cn

OPTICAL RAY MATRICES

In our previous paper [5], the propagation between different optical elements is done by OPC code in which the spherical mirror is implemented by applying phase shift to the field. However, there is no other cavity mirror module. While optical ray matrices or "ABCD" matrices are widely used to describe the propagation through paraxial optical elements. Therefore the special cavity mirror can also be described by this ABCD matrices. Taking spherical mirror as an example, the equivalent matrix is

$$T = \begin{pmatrix} 1 & 0 \\ -2/R & 1 \end{pmatrix} \tag{1}$$

where R is the radius of curvature of spherical mirror. It is positive for concave mirror while negative for convex mirror. Thus for toroidal mirror that with different curvature radius in sagittal and tangential plane, the matrices are given by

$$T_x = \begin{pmatrix} 1 & 0 \\ -\dfrac{2\cos\alpha}{R_x} & 1 \end{pmatrix} \quad T_y = \begin{pmatrix} 1 & 0 \\ -\dfrac{2}{R_y\cos\alpha} & 1 \end{pmatrix}$$

where α is the incidental angle, R_x and R_y are the sagittal and tangential radius, T_x, T_y are the matrix in horizontal and vertical direction, respectively.

However, there is a minimal propagation distance limitation in OPC code due to the implementation of algorithm on a discrete grid. So the toroidal matrix in combination with Fresnel propagation in free space is considered as a whole optical element. To simplify the calculation, we assume that the light propagation in the normal incidence angle ($\alpha = 0$). Then the corresponding horizontal and vertical matrices are

$$T_x = \begin{pmatrix} 1 & l \\ 0 & 1 \end{pmatrix}\begin{pmatrix} 1 & 0 \\ -2/R_x & 1 \end{pmatrix} = \begin{pmatrix} 1-2l/R_x & l \\ -2/R_x & 1 \end{pmatrix}$$

$$T_y = \begin{pmatrix} 1 & l \\ 0 & 1 \end{pmatrix}\begin{pmatrix} 1 & 0 \\ -2/R_y & 1 \end{pmatrix} = \begin{pmatrix} 1-2l/R_y & l \\ -2/R_y & 1 \end{pmatrix}$$

with l being the drift distance from toroidal mirror to waveguide port in free space region. Through these two optical matrices, the propagation from toroidal mirror to the waveguide incident port is clear. So the wGeneis in combination with OPC code can still be used to make a numerical simulation of waveguide FEL oscillator in the special mirror case. Thus this method is applied in the FELiChEM facility to improve its output power in far infrared wavelength range.

SIMULATION RESULTS

The waveguide of FELiChEM FIR branch only covers the undulator region with longitudinal length L = 2.24 m.

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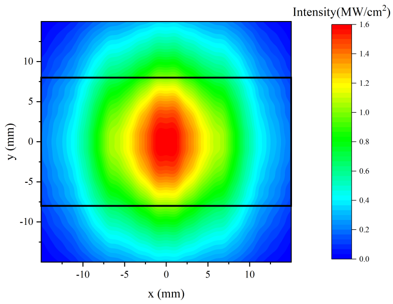

Figure 1: The truncation loss at the waveguide port when the wavelength is 170 μm with spherical mirror. The black rectangle represents the waveguide transverse size.

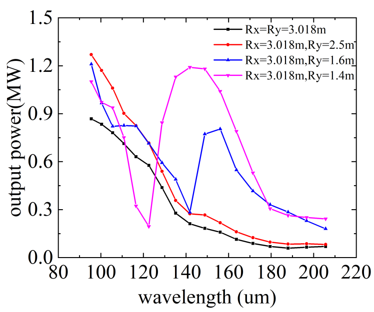

Figure 2: The output power as a function of wavelength at different cavity mirror curvature.

The transverse size of waveguide is 30 mm and 16 mm in horizontal and vertical direction, respectively. Two spherical mirror of R = 3.018 m is used to form a 5.04 m long FIR cavity. However, the existence of waveguide in vertical direction will bring truncation loss when the optical field is reflected from mirror to waveguide port. In Fig. 1, the optical transverse light spot is given at waveguide port. It can be seen that the reflected light is cut off by the waveguide in vertical direction. Obviously, this truncation loss will cause the decrement of FEL oscillator output power. Because waveguide vertical size is limited to offer enough undulator magnetic field, a possible way is to decrease the focal distance of cavity mirror in vertical direction.

Therefore the toroidal mirror is considered in FELiChEM FIR branch. The simulation result is shown in Fig. 2. The black solid line is spherical cavity mirror with $R_x = R_y =$ 3.018 m. Then the value of R_y is changed to reduce the truncation loss at the waveguide port. The simulation result shows that output power is increased with the decreasing with R_y. The maximum increment is about 6.4 times around 150 μm when the curvature radius is at R_y = 1.4 m.

To make a comparison, the transverse size of light at waveguide port after mirror reflecting from R_y = 1.4 m is given in Fig. 3. There is little truncation of light spot size in vertical direction at the waveguide port. It is obvious that the truncation loss can be reduce by choosing a proper curvature radius at given wavelength.

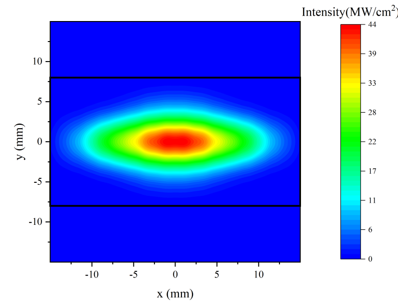

Figure 3: The truncation loss at the waveguide port. The black rectangle represents the waveguide transverse size.

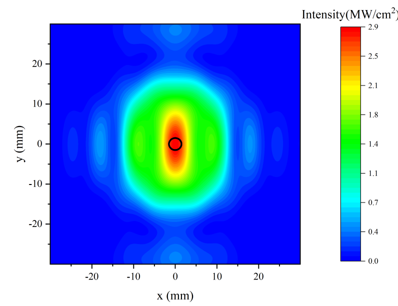

Figure 4: The transverse distribution of optical light intensity in the coupling mirror at 120 μm.

Though mostly the output power at R_y = 1.4 m is higher than that of spherical case in far infrared wavelength case, there is an exception region around 120 μm. This spectral gap can be explained by the waveguide effect that causing a low coupling efficiency from the hole. The light distribution at the coupling mirror is given in Fig. 4. The intensity distribution at center is lengthening due to the existence of two peaks along vertical direction.

To explain the optimum value of R_y = 1.4 m, we make a simple assumption neglecting the effect of diaphragm and coupling hole. Then the light path from waveguide to the reflected mirror and then back to the waveguide port can also be described by a optical matrix. The vertical direction is given as

$$T_y = \begin{pmatrix} 1 & l \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -2/R_y & 1 \end{pmatrix} \begin{pmatrix} 1 & l \\ 0 & 1 \end{pmatrix}$$
$$= \begin{pmatrix} 1-2l/R_y & 2l(1-l/R_y) \\ -2/R_y & 1-2l/R_y \end{pmatrix}$$

When the curvature radius $R_y = l$, it can be simplified as

$$T_y = -\begin{pmatrix} 1 & 0 \\ 2/R_y & 1 \end{pmatrix}.$$

It is clear that this matrix is in equivalent to a convex mirror as Eq. (1) shown. Therefore when the curvature radius of toroidal mirror equals to the drift distance, it is in equivalent to a convex mirror. Thus there is little transverse truncation loss at the waveguide port.

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CONCLUSION

In this paper, the waveguide effect with special cavity mirror, such as toroidal, cylindrical case are developed based on the wGenesis in combiantion with OPC code. Then this method is applied to analyze the FELiChEM waveguide effect at far infrared wavelength. The results show that the optimum output power is achieved when vertical curvature radius equals to the drift distance between waveguide and cavity mirror. It is in well agreement with the propagation matrix theory.

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