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SPECTRAL GAP IN THE MIDDLE INFRARED FEL OSCILLATOR OF FELiCHEM*

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Abstract

A phenomenon of spectral gap is observed in the Middle infrared Free-electron laser oscillator (FELO) of FELiCHEM: the laser power falls down at the particular wavelength. Starting with the experimental data, this paper focuses on the simulation calculation and the effect from using the partial waveguide. The relationship between waveguide and spectral gap is revealed.

INTRODUCTION

Free-electron laser oscillators (FELOs) have been around since 1977 providing not only a test bed for the physical experiments of Free-electron Laser (FEL) but also as a workhorse of scientific research [1, 2]. As an optical facility, high power and efficiency, quasi monochromaticity and continuously tunable wavelength make FEL facility stand out from other optical facilities. Spanning the wavelength range from the millimeter region to the ultraviolet, dozens of FELOs are presently operating around the world. FELO is the most common FEL operating mode in the infrared region such as FELIX [3], CLIO [4] and FELiCHEM [5]. FELiCHEM (see Fig. 1) is a facility for energy and chemical scientific researches constructed by the National Synchrotron Radiation Laboratory (NSRL) in China. The FEL of FELiCHEM generates 2.5 -200 μm laser for photo dissociation, photo excitation and photo detection experimental stations. As shown in Fig. 2 Two FELOs driven by one radio frequency linear accelerator are used to generate mid-infrared (MIR)(2.5 -50 μm) and far-infrared (FIR)(40-200 μm) lasers.

Figure 1: Photo of the core device of FELiCHEM.

A phenomenon of spectral gap was observed in the MIR FELO of FELiCHEM when in commissioning and operation. The output laser power falls down quickly and even

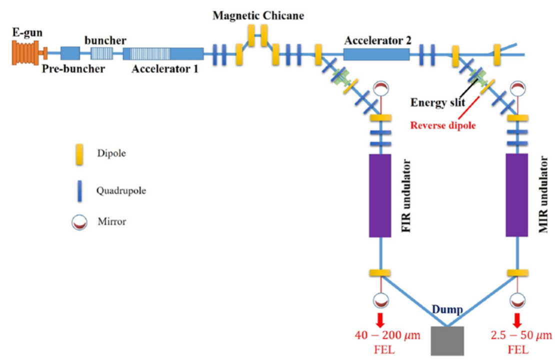

Figure 2: Schematic of FELiChEM's FEL layout.

be nearly disappeared around the particular wavelength region. This phenomenon influences the tunable range of laser, limiting the users' experimental researches such as spectral scanning. This kind of phenomenon also appears in other infrared FEL facilities [6, 7]. In this paper, we probe into the causes and rules of spectral gap. Based on the experimental data, combined with simulation analysis and Prazeres *et al.*'s explanation [8], the following content is obtained.

EXPERIMENTAL DATA OF MIR FELO IN FELiCHEM

The main parameters of the MIR FELO (Fig. 3) are as follows [5]: The period length of undulator is 46 mm and period number is 50; The length of the oscillator's cavity is 5.04 m; The reflectivity of the mirror is 98.5% and the curvature radius of the mirror is 2.756 m. NdFeB permanent magnet planar undulator is symmetrically placed in the center of the optical resonant cavity which is composed of two face-to-face spherical mirrors. The device adopts the central hole coupling output scheme. In order to adapt to the different spots' size of the mirror at any working wavelengths, there are four different diameter (1.01.5/2.5/3.5 mm) of coupling holes on the mirror downstream of the resonator.

With the energy of injected electron beam fixed, working wavelength can be only adjusted by changing the magnetic gap of the undulator. Four optimized electron energies are selected, covering the wavelength range of 2.5 -50 μm. Figure 4 shows the experimental data of mid infrared free electron laser. It is obvious that macropulse energy of the output laser dramatically decreases to the lowest at the wavelength of 20.5 μm. On other wavelengths, macropulse energy is more than 10 mJ. On the other hand, Fig. 5 expresses the situation of MIR FELO from the average power. The existence of

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spectral gap around 20 μm can also be clearly seen. Figures 4 and 5 are different in the selection of incident electron beam energy and waveguide structure size.

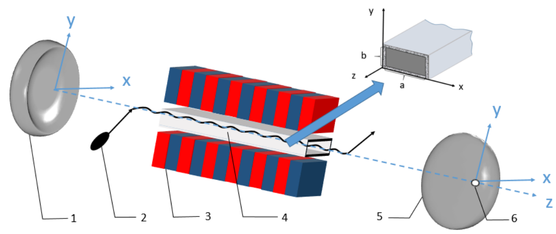

Figure 3: Schematic of FELiCHEM's MIR FELO layout.

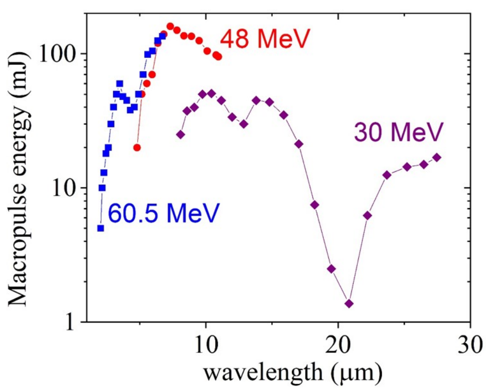

Figure 4: Macropulse energy of FELiCHEM middle infrared laser (measured by energy meter in Nov. 2020) (waveguide(a×b): 35 ×10 mm).

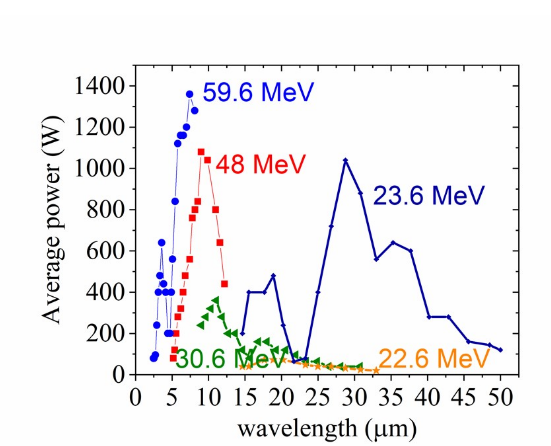

Figure 5: Average power of FELiCHEM middle infrared laser (measured by power meter in Jun. 2020) (waveguide(a×b): 20 ×10 mm).

At the normal operating wavelengths, the light field distribution on the downstream resonator mirror is Gaussian or approximate Gaussian distribution. Due to the adoption of central hole coupling output method, the output laser's power is high on those wavelengths. However, the light field is no longer Gaussian distribution at the spectral gap.

EXPLANATION AND SIMULATION

The Existence of Optical Waveguide

In the infrared spectral region, due to the long wavelength, the diffraction loss is large in the FELOs [9]. To tackle this barrier, researchers usually adopt a partial optical waveguide in the direction parallel to the magnetic field to constrain the optical field. The problem can be solved by replacing the small-scale and flat vacuum chamber with the optical waveguide which has smooth inner wall and high conductivity. In the optical cavity, the group velocity of light diminish, the light's slippage relative to the electron beam decreasing. The waveguide concentrates the optical field to the axis, which enhances the overlap with the electron beam and increases the optical field gain [10].

However, according to Prazeres *et al.*'s explanation, the phenomenon of 'spectral gap' appears due to the addition of optical waveguide. That is because the waveguide changes the optical field mode in the resonant cavity, resulting in the weak optical field intensity near the centre hole on the coupling output mirror at the spectral gap [8]. The configuration of the optical waveguide produces a particular combination of eigenmodes TEq and TMq [8]. As R. Prazeres *et al.* said, when sweeping the operating wavelength, a phase difference of 2 in a cavity round-trip accounts for the wavelength differences between two successive gaps. And the wavelength difference $\delta\lambda$ can be regarded as [8]:

$$\delta\lambda = \lambda' - \lambda = \frac{b^2}{2L}, \qquad (1)$$

where λ is chosen to the wavelength of a spectral gap and then λ' is the next 'spectral gap', L is the waveguide length and b, which can be called waveguide gap, is the waveguide aperture in y-axis. For one FELO facility, the wavelength difference is usually smaller than the designed operating wavelength range. Furthermore, the wavelength position formula of spectral gap is as follows:

$$\lambda = \frac{b^2}{2L}(2n+1)(n = 0, 1, 2, ...). \qquad (2)$$

The MIR FELO of FELiCHEM selects the waveguide with a gap of 10 mm (b=10 mm). It can be calculated theoretically that the wavelength at the spectral gap within the operating wavelength range is 20.8 μm. The theory is consistent with the actual situation, which can be confirmed in Figs. 4 and 5.

Simulation With Genesis and Optical Propagation Code

In the light of the FELiCHEM's set parameters, the MIR FELO is simulated by software modified *GENESIS* and *Optical Propagation Code*(*OPC*). *GENESIS* [11] is a time-dependent three-dimensional FEL code,and the modified *GENESIS* adds boundary conditions which are used to represent the waveguide to the original one. The *OPC* [12] implements wavefront propagation of optical fields and is

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tailored to work together with *Genesis* to simulate FEL systems.

One of the simulation results is shown in Fig. 6. With the energy of injected electron beam is 25 MeV, there is a spectral gap around the wavelength of 20 µm. This situation is simulated under the assumption that the waveguide structure is 30 × 10 mm.

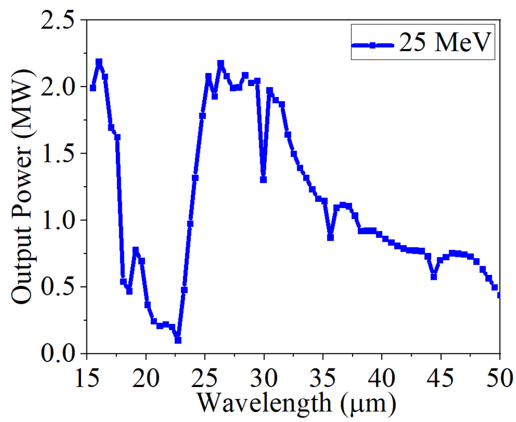

Figure 6: Simulation of FELiCHEM middle infrared laser (waveguide(a×b): 30 × 10 mm).

DISCUSSION

The agreement between experiment, simulation and theoretical formula calculation is acceptable. What they have in common is that the position of spectral gap (λ=20 µm) is determined by the waveguide gap (b=10 mm). The energy and power of the laser output at the waveguide gap are greatly reduced. When the spatial structure and undulator gap are satisfied, the waveguide gap is supposed be changed appropriately to adjust the position of the spectral gap and reduce its influence on the wavelength tuning.

CONCLUSION

This phenomenon widely exists in FELOs with waveguide, and the position of spectral gap can be determined after the structure parameters of the device are determined. This phenomenon affects users' experiments such as spectral scanning. In FELiCHEM middle infrared laser, the spectral gap where the output laser energy and power are greatly reduced is around 20 µm.

REFERENCES

[1] G. R. Neil, "FEL Oscillators", in *Proc. 20th Particle Accelerator Conf. (PAC'03)*, Portland, OR, USA, May 2003, paper TOAC002, pp. 181–185.

[2] B. N. Murdin, "Far-infrared free-electron lasers and their applications", *Contemporary Physics*, vol. 50, pp. 391–406, 2009. doi:10.1080/00107510902733856

[3] A. F. G. Van Der Meer and M. J. Van Der Wiel, "Mid-IR FEL User Facility FELIX", *Appl. Spectrosc.*, vol. 51, pp. 574–575, 1997.

[4] J. M. Ortega, "The CLIO Infrared FEL Facility", *Synchrotron Radiation News* , vol. 9, no. 2, pp. 20–33, 1996. doi:10.1080/08940889608602868

[5] H. Li *et al.*, "Hefei infrared free electron laser facility", *Chinese Journal of Lasers*, vol. 48, p. 1700001, 2021. doi:10.3788/cjl202148.1700001

[6] L. Y. Lin and A. F. G. Van Der Meer, "Design of a short-pulse, far-infrared free electron laser with a highly overmoded waveguide", *Review of Scientific Instruments*, vol. 68, no. 12, pp. 4342–4347, Dec. 1997. doi:10.1063/1.1148393

[7] P. Michel *et al.*, "The Rossendorf IR-FEL ELBE", in *Proc. 28th Int. Free Electron Laser Conf. (FEL'06)*, Berlin, Germany, Aug.-Sep. 2006, paper TUCAU02, pp. 488-491.

[8] R. Prazeres, F. Glotin, and J.-M. Ortega, "Analysis of periodic spectral gaps observed in the tuning range of free-electron lasers with a partial waveguide", *Physical Review Special Topics - Accelerators and Beams*, vol. 12, no. 1, p. 010701, Jan. 2009. doi:10.1103/physrevstab.12.010701

[9] Y. Zou *et al.*, "Simulation of the resonator with inserted scraper output coupler for the far-infrared FEL", *High Power Laser and Particle Beams*, vol. 15, no. 12, pp. 1167–1170, 2003.

[10] X. Shu *et al.*, "Improving the net gain of far infrared free electron laser by using waveguide", *Annual Report of China Academy of Engineering Physics*, vol. 1, p. 250, 2004.

[11] Genesis, http://genesis.web.psi.ch/index.html

[12] Optical Propagation Code (OPC), https://lpno.tnw.utwente.nl/opc-draft/.