DEVELOPMENT OF A COMPACT CHERENKOV FREE-ELECTRON LASER IN TERAHERTZ SPECTRAL RANGE

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Abstract

A Cherenkov free-electron laser (CFEL) generating terahertz radiation is now being developed under the joint research of Osaka Sangyo university and Kansai university. The main feature of the CFEL is its compactness. Micro-beamlets from Spindt-type field emitter array are accelerated up to 50 keV and then injected into a silicon resonator with a path of 50 to 150 μ m spacing through which electrons propagate. Omitting the evacuation system and power supply, the size of CFEL section, including electron gun and resonator, is about $1 \times 1 \times 4$ cm^3. For the generation and the transport of the electron beam few μm in diameter, we investigated characteristics of the Spindt cathode, beam focusing by electrode and the magnetic field. A carbon nanotube field emitter was also tested for future application.

INTRODUCTION

Cherenkov free-electron lasers (CFELs) are one of the great candidates for compact tunable radiation sources. A pioneer work had demonstrated CFEL in 100 GHz frequency range using an electron beam with 35 to 75 keV acceleration energy [1]. In order to increase the operation frequency to terahertz frequency range, it is straightforward to scale down the optical resonator of CFEL. Fig. 1 shows a schematic view of a compact CFEL. Electron beamlets several μm in diameter are accelerated to 50 keV and then injected into a dielectric resonator. Electron beamlets passing through a channel bored in the dielectric resonator excite the Cherenkov radiation and interact with the evanescent part of that radiation.

The resonant frequency is determined principally by the radius of the channel: the resonant wavelength coms to severalfold of the channel radius. The dispersion curve of the evanescent wave in a circular dielectric waveguide is shown in fig. 2 with the dispersion of the light in vacuum and a beam-mode for 40 keV electron [2]. Because electrons moving along the channel transfer its kinetic energy to the radiation field via the interaction with the longitudinal component of the radiation field, the TM-mode which has that field component is important in such CFEL. Thus the dispersion relation for the TM_{01}-mode is shown in the figure. For the case of R_d=25 μm, the resonant frequency is 1.6THz. Note that the dispersion relations are scalable with the channel radius, thus the resonant frequency increases

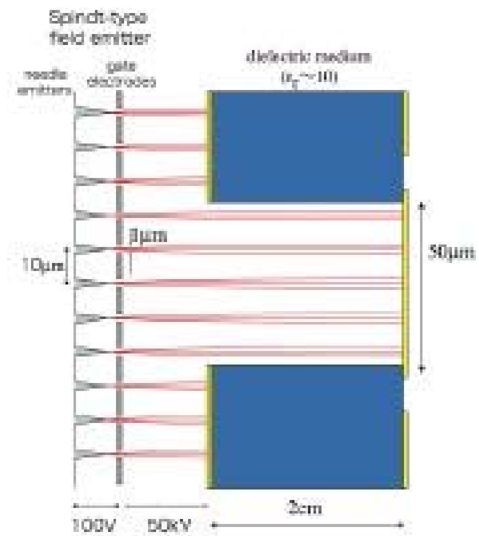

Figure 1: Schematic view of compact CFEL.

with decreasing the channel radius. CFELs are, therefore, capable to be operated in mid-infrared to sub-millimeter spectral range.

Our research aims a compact, more ambitiously, palmtop CFEL that can generate the radiation over the infrared spectral area. As the first step, we are developing the electron beam source which can produce μm beamlets. In following section, a CFEL test bench and experimental studies of the beam focusing will be described.

CFEL TEST BENCH

To produce the electron beam whose radius is order of micrometer, we used a Spindt cathode,[3] which contains 100,000 pairs of ultrasmall needles and gate electrodes in a 1 mm diameter array. Each pair of needle and electrode generate electron beamlet with diameter around 1 μm, and these tiny electron guns are arrayed with a spacing of 10 μm. Due to the needle-gate configuration and the high operation current density, Spindt cathode generates a diverging beam as shown in fig. 3. Therefore, the beam transport is the critical issue.

Figure 4 and fig.5 show the schematic view and the picture of a developing CFEL test bench, respectively. This system employs the magnetic field for the beam focusing. Main components, such as Spindt cathode, collector electrode and a optical resonator, are installed inside the bore

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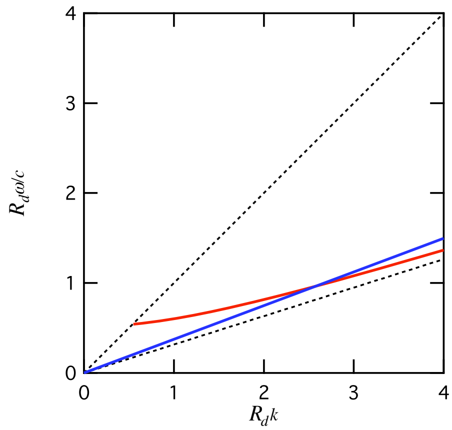

Figure 2: Dispersion relations of the evanescent wave for TM_{01}mode. The relative dielectric constant of the medium is 10.(red) Both axes are multiplied by the channel radius (R_d=25 μm) for the normalization. The blue solid line shows the dispersion of 40 keV beam mode. Upper and lower dashed lines denote the dispersion of the light in vacuum and the light in the dielectric medium, respectively.

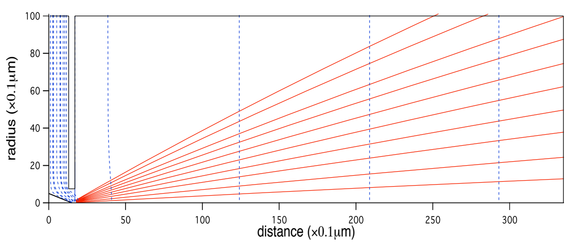

Figure 3: Calculated trajectories of electrons emitted by Spindt cathode. Red lines show the electron trajectories and Blue lines represent the equipotential lines. E-gun code was used for the calculation.

of a super conducting coil, which can produce magnetic flux density up to 5 T. The footprint of the whole system including the compressor unit for super conducting magnet is about 1 $\times$1 m^2.

Electron beamlets generated at the grounded Spindt cathode needles are accelerated toward the collector electrode, which is followed by the optical resonator. The resonator consists of a pair of silicon slabs gapped by thin spacers with thickness of 50, 100 or 150 μm. The resonant frequency increases from several hundreds GHz to few THz as decreasing the gap spacing. The end edges of slabs facing to the cathode are coated with Al and work as both the collector electrode and resonator mirror, while the other edges are left uncoated to extract Cherenkov radiation. One side of the gap between the slabs facing to cathode is opened for the beam injection, while the other side is blocked by the spacer for beam dumping and reflecting back of a part of radiation. The length of the laser interaction region is 2 cm.

Figure 6 shows the time trace of the gate voltage and the beam current. Pulsed voltage up to 100 V is applied to the gate electrode of Spindt cathode to generate a few

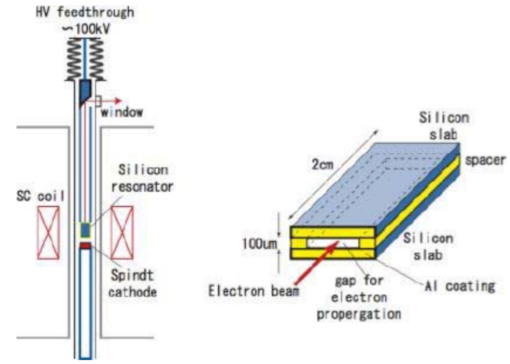

Figure 4: Schematic view of the CFEL test bench and the resonator. The left and right figures show the schematic view of the whole system and the detailed view of the resonator, respectively.

Figure 5: Picture of the CFEL test bench. The high voltage feedthrough, the 2-axis manipulator for resonator alignment and cryostat of the super conducting coil can be seen. The height and footprint of the device are 1.9 m (including a 0.7 m-height pedestal) and 0.7$\times$0.7 m^2, respectively.

milli-amperes beam current. The raise time of 50 μs was determined by the capacitance of the power feed cable and 100 kΩ resistance for current monitoring, and will be shorten by reducing the resistance in the laser experiments that higher beam current will be required. For the operation above the beam current shown in the figure, we suffered from the serious degassing and the following brake down. Such undesirable events were remarkable especially when the magnetic field was applied. This system is under aging process.

FOCUSING ELECTRODE

Because the magnetic focusing requires a large and expensive magnet, we also explored beam focusing using mid-electrode. A mid-electrode was located at a distance of 13 mm from the cathode. The spacing between the mid-

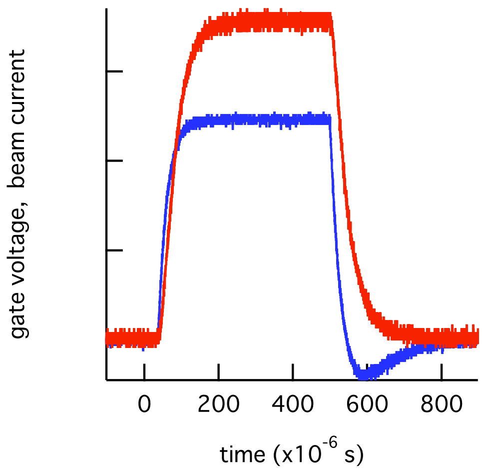

Figure 6: Time trace of the gate voltage (red) and the beam current (blue). Peak voltage is 50 V and peak current is 81 μA.

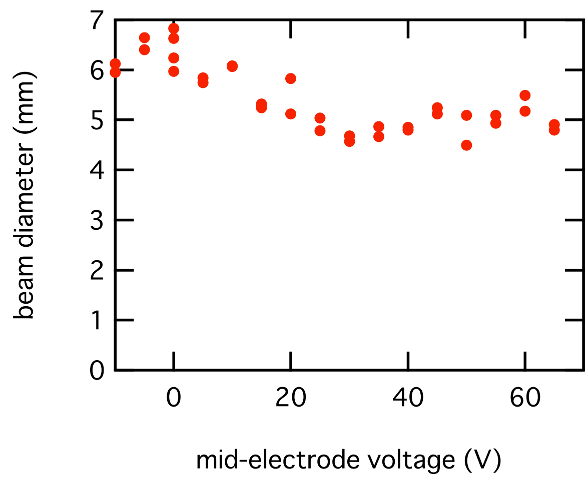

Figure 7: Beam diameter as a function of the mid-electrode voltage. During experiment, the collector voltage was held at 10 kV and pulsed 65 V voltage was applied to the gate electrode of Spindt cathode.

electrode and the collector electrode was set to 30 mm. Mid-electrode had a hole 5 mm in diameter through which the electrons pass through. The beam spot size at the collector electrode was evaluated from the fluorescence image on a phosphor screen placed at collector electrode. Figure 7 shows the beam diameters as a function of the mid-electrode voltage. The collector electrode voltage was held at 10 kV during the experiment. The gate voltage was set to 65 V and the pulse width was 10 ms to obtain luminance enough to observe. Note that these results show the diameter of the whole beam emitted from 100,000 tiny needles: the fine structure formed by each beamlet was smoothed out due to poor resolution of the measurement system. It is seen that the beam diameter decreases with mid-electrode voltage up to 30 V and then slightly increases with the voltage. It is inferred that the beam is over focused with the mid-electrode voltage above 30 V. This result indicates that the beam focusing by the focusing electrode is not enough to produce the electron beam with micrometer diameter. We are on the way to design optimal electrode configuration combined with the magnetic field configuration to find the reasonable focusing system.

CARBON NANOTUBE CATHODE

To develop the brighter electron beam source, we also tested a carbon nanotube cathode. As this test is a preliminary one: powdered carbon nanotubes were smeared over a 0.5 mm diameter plate of stainless steel and the gate electrode was not installed. Due to the lack of the gate electrode, the spacing between the cathode and the collector electrode was set to 0.2 mm to produce electric field enough for the field emission. Figure 8 shows the beam current vs. the collector electrode voltage. Electron emission stars at a voltage of 2.2kV and the current reaches to 2.4mA at 4.4 kV. Above 4.4 kV acceleration voltage, serious outgassing degraded the vacuum condition, thus we limited the supply voltage to this extent. It is worth to mention that the beam current was stable for long period of these experiment in spite of D.C. operation. Taking into account the fact that operation of Spindt cathode with D.C. 1 mA leads serious damage on Spindt cathode, we conclude that carbon nanotube cathodes are capable of generating denser electron beam. Installation of the gate electrode is the key issue for practical application.

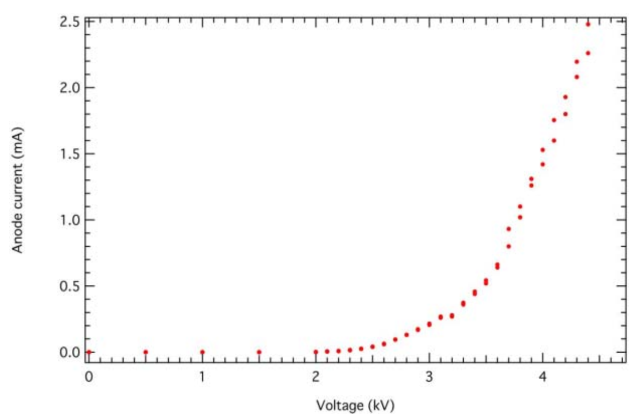

Figure 8: V-I curve for carbon nanotube cathode. D.C. voltage up to 4.4 kV was applied to the collector electrode.

SUMMARY AND RESEARCH PLAN

A compact THz CFEL driven by 50 keV electron beam is under development. Use of Spindt cathode and focusing of the electron beam are key technologies of this device. A CFEL test bench using super conducting coil for beam focusing was commissioned and is under conditioning. Beam focusing by mid-electrode was also studied. To find the reasonable focusing system, we are investigating the beam focusing by the combination of the magnetic field and mid-electrode. First CFEL test will be started using high magnetic field up to 5 T after the aging conditioning of the test bench. The output frequency will be gradually increased from several hundreds GHz to few THz by reducing the gap spacing of the resonator. It is also planned to study Smith-Percell FEL and Cyclotron radiator on the test bench.

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