Experimental Study on Backward Wave Oscillation Based on Cylindrical Surface Wave of Smith-Purcell Free Electron Laser*)

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Backward wave oscillation based on a cylindrical surface wave of Smith-Purcell free electron laser (SP-FEL) is demonstrated. The SP-FEL is composed of a metal cylinder having a periodically corrugated wall and a surrounding hollow straight waveguide. Corrugation parameters are those used in K-band backward wave oscillators (BWOs). The metal cylinder has a surface wave due to the corrugation. The cylindrical surface wave is excited by an axially injected coaxial annular beam. Radiations due to the backward wave oscillation based on the cylindrical surface wave are examined in a weakly relativistic region less than 100 kV. An oscillation starting voltage exists for the backward wave oscillation as in the case of hollow oversized BWO. The frequencies are in K-band and are determined by the cylindrical corrugation. Radiations up to tens of kW are obtained.

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1. Introduction

Smith-Purcell free electron lasers (SP-FELs) have been studied as a family for tunable electromagnetic sources in the far-infrared or terahertz (THz) region [1–7]. SP-FELs using a beam of scanning electron microscope (SEM) with around 30-35 kV voltage and current up to mA order attract attention to develop a compact THz source [2–7]. When the electron beam passes near the grating surface, a spontaneous SP radiation may be excited. In Ref. [2, 3], "super-radiant SP emission" has been reported. Since the grating is a slow-wave structure (SWS), it has a surface wave. And the resonant interaction of beam with the surface wave is essential to the super-radiant SP emissions [5]. The interaction may result in a backward wave or traveling wave operation depending on the group velocity of the surface wave. Given the relatively low energy and the intrinsic feedback, the backward wave oscillation is important for SP-FELs.

The super-radiance has not always been observed [4]. Requirements for the SP radiations based on the backward oscillation have been examined [5, 7]. The electron beam is desirable to be flat and cover the entire surface of flat grating. However, beams in realistic SP-FELs have a circular cross section and partially cover the grating surface. Moreover, a proper output section is required to collect the emission of SP-FEL. In a recent experiment satisfying the requirements [6], the backward operation of SP-FEL excited by the SEM beam is experimentally confirmed for the first time by preparing an output section composed of parabolic mirror and Michelson interferometer.

The SP devices described above have a plane geometry. Cylindrical systems are successfully used in oversized BWO [8–10]. An idea of SP-FEL incorporating the advantages of cylindrical SWS and BWO seems to be very attractive. On the other hand, a negative aspect has been pointed out that efficient beam interactions with an axisymmetric inner corrugation could not be expected [11]. Backward wave oscillations based on cylindrical surface waves are still unclear and should be examined to develop cylindrical SP-FELs.

In this work, backward wave oscillation based on cylindrical surface wave of SP-FEL is studied. The cylindrical SP-FEL is composed of a periodically corrugated metal cylinder and an annular beam. Uniformly distributed annular beam is generated by a novel disk cold cathode in a weakly relativistic region less than 100 kV [10, 12]. The current is much higher as compared to plane SP-FELs. The cylindrical corrugation has a rectangular shape with parameters used in K-band BWO [10]. The backward wave oscillation is experimentally examined by exciting the cylindrical SP-FEL using a coaxially injected annular beam.

2. Cylindrical Corrugation

We use a cylindrical corrugation like Fig. 1. The corrugation parameters are average radius R_0, corrugation amplitude h, corrugation width d and periodic length z_0. The corrugation wave number is given by $k_0 = 2\pi/z_0$. Cylindrical corrugation is surrounded by a smooth hollow waveguide with radius R_1 to collect and extract the radiations. In Fig. 2, the dispersion curves of cylindrical surface wave

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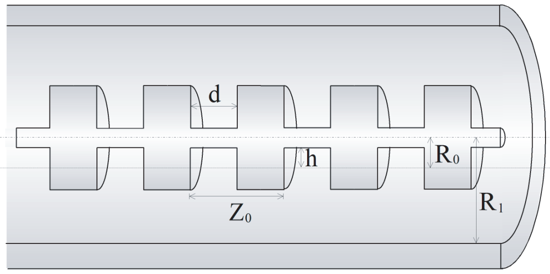

Fig. 1 Schematic diagram of cylindrical SP-FEL composed of cylindrical corrugation and surrounding smooth hollow waveguide.

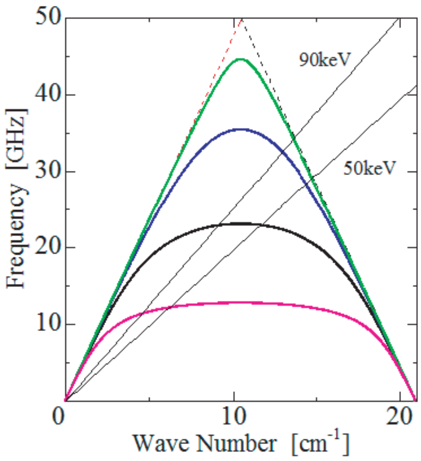

Fig. 2 Dispersion curves of cylindrical surface wave for corrugated cylinder with R_0 = 8.4 mm, d = 1.5 mm and z_0 = 3.0 mm. Values of h are 0.275, 0.55, 1.1 and 2.2 mm, from the top. Beam lines are plotted as a reference. Dotted lines are light lines.

are plotted with R_0 = 8.4 mm, d = 1.5 mm and z = 3.0 mm, varying h from 0.275 mm to 2.2 mm. According to Floquet's theorem, known as Bloch's theorem in solid-state physics, the dispersion curves of spatially periodic SWSs are periodic in wave number space (k_z-space) with a prided of k_0 = 20.9 cm^{-1}. By increasing h, an upper cutoff frequency at π point ($k_z z_0 = \pi$) decreasing.

3. Experimental Setup

The experimental setup is schematically shown in Fig. 3. Output voltage up to 100 kV from the pulse forming line is applied to a cold cathode. A uniform axial magnetic field B_0 for the beam propagation is provided by ten solenoid coils. In this paper, B_0 is set to 0.82 T. The microwave radiations from the output window are picked up by a rectangular horn antenna typically located 600 mm away from the output window. The detected microwave signal is split into two branches by a multi-hole directional coupler. One consists of a short waveguide and forms a prompt signal. The other branch is a delay line and forms a delayed signal. The delay line in this paper is composed

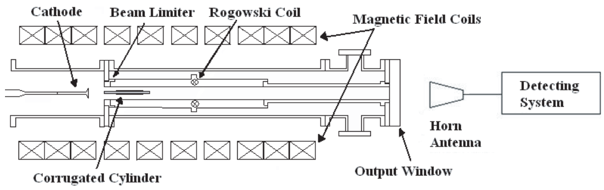

Fig. 3 Schematic diagram of experimental setup.

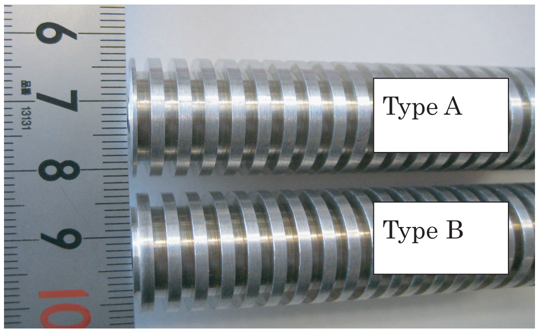

Fig. 4 Cylindrical corrugations used in our experiment. Both ends are tops (Type A) and bottoms (Type B) of corrugation with R_0 = 8.4 mm, d = 1.5 mm, z_0 = 3.0 mm and h = 1.1 mm. The total length of corrugation is $20z_0$.

of 18.4 m long waveguide with cutoff frequency 17.4 GHz.

A disk cold cathode proposed in Refs. [10, 12] is used. It can generate uniformly distributed annular beams in a weakly relativistic region. Injected electron beam has an annular shape, which is examined by observing burn patterns in thermally sensitive paper obtained by intersecting the beam. The diameter of annular beam is nearly the same as the cathode diameter. The thickness of annular is typically 2-3 mm.

Two types of cylindrical corrugations shown in Fig. 4 are used. They are made of aluminum. The corrugation parameters correspond to K-band oversized BWO in Ref. [10]. The radius of the surrounding hollow waveguide is R_1 = 15 mm. The cylindrical corrugation is located at the center of the hollow cylindrical waveguide by using supports on the input and output sides of the corrugated cylinder. The support on the beam input side acts as a beam limiter. The limiter's outer and inner diameters are φ28 mm and φ19 mm, respectively.

4. Experiment of Backward Wave Oscillation Based on Cylindrical Surface Wave

Figure 5 shows an example of detected signals. The beam voltage and current are about 68 kV and 64 A, at the microwave peak time. The delay time of delayed signal after passing a 18.4 m long delay line is 106 nsec and the operation frequency is estimated to be 23 ± 2 GHz.

Figure 6 shows the dependence of the microwave power on the beam voltage with Type B corrugated cylin-

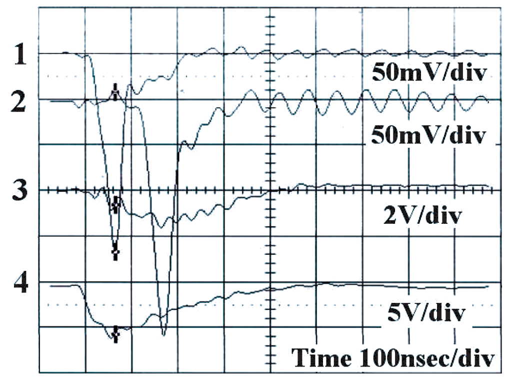

Fig. 5 Waveforms of measured signals: 1, prompt signal; 2, delayded signal; 3, beam current; and 4, beam voltage.

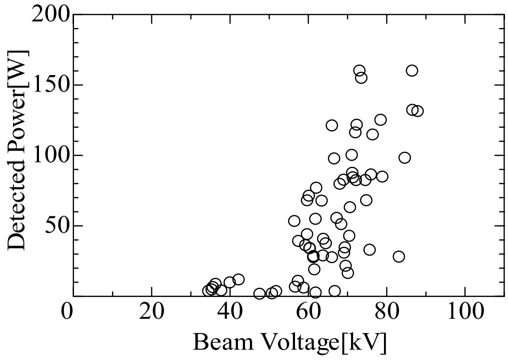

Fig. 6 Detected power versus cathode voltage with Type B corrugated cylinder Cathode diameter is φ20 mm.

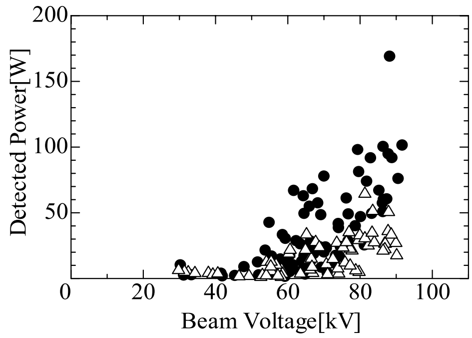

Fig. 7 Detected power versus cathode voltage with Type A corrugated cylinder. Cathode diameter is φ20 mm (closed circles) and φ23 mm (open triangles).

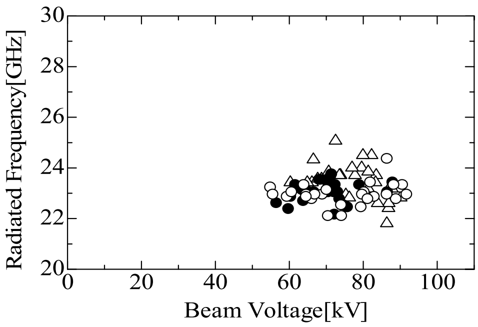

Fig. 8 Frequency versus beam voltage. Open and closed circles and open triangles are the same as Figs. 6 and 7.

der. The oscillation starts above about 35 kV. Meaningful microwaves are not observed with the lower voltages than this critical value. The output power increases by increasing the cathode voltage up to about 90 kV. Intense radiations estimated to be in tens of kW level are observed in the voltage region of 60-90 kV.

Oscillation starting conditions for oversized hollow BWOs has been studied theoretically and experimentally [9, 10, 13, 14]. There exists a starting current. Another critical parameter so called starting voltage also exists and is studied theoretically and experimentally [13, 14]. In the K-band oversized BWOs, the starting voltage becomes more critical than the starting current. Figure 6 shows that a starting voltage exists even in the oscillation based on the cylindrical surface wave of SP-FEL.

The surface wave is restricted to the cylindrical corrugation with the total length of $20z_0$, and may be reflected at both ends of corrugation. To examine the end effects, radiations with Type A corrugated cylinder are used in Fig. 7. The radiation power with Type A reaches maximum at the higher beam voltage than Type B case. On the average, the power level of Type A is lower than that of Type B. The difference in Type A and B is only the end condition of corrugation. The surface wave is formed satisfying the boundary conditions. The corrugation ends affect the Floquet's harmonics, including the lowest harmonic which couples to the beam. According to Ref. [15], the lowest harmonic contribution to the surface wave may decrease from Type B to Type A. This could cause the observed change in the power level.

Dependence of the oscillation due to the cylindrical surface wave on the cathode diameter is also shown in Fig. 7. The radiation with φ23 mm diameter decreases about 2 to 3 times than that with φ20 mm. By changing the cathode diameter from φ20 mm to φ23 mm, the distance between the beam and cylindrical surface may change by nearly 1 mm and affects the oscillation strongly. The attenuation length of the surface wave in the radial direction around the π point is estimated to be about 2 mm for the K-band corrugation. Hence, the change in the beam radius may be relatively large.

Measured frequencies are plotted in Fig. 8. The frequencies are mostly distributed from 22 to 24 GHz for Type A and B corrugations with φ20 mm cathode. And the data vary slightly wider for φ23 mm cathode. The estimated error in the frequency measurement is ± 2 GHz. Hence, it can be concluded that the frequency of oscillation based on the cylindrical surface wave is about 23 ± 2 GHz. The observed frequency is in a good agreement with theoretically expected one from the cylindrical surface wave in Fig. 2.

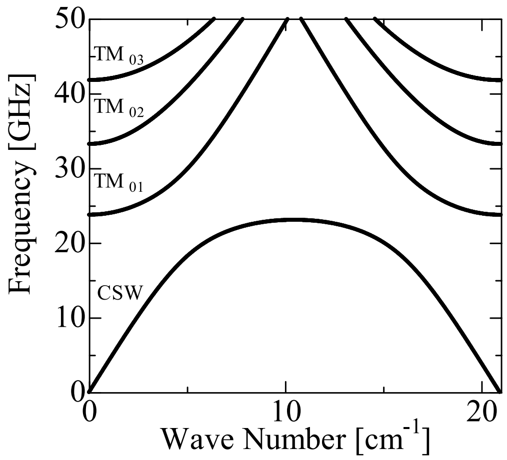

Fig. 9 Dispersion curves of corrugated cylinder surrounding hollow straight waveguide. Corrugation parameters of cylinder are R_0 = 8.4 mm, d = 1.5 mm, z_0 = 3.0 mm and h = 1.1 mm. The radius of surrounding waveguide is 15 mm.

5. Discussion and Conclusion

When the surface wave is reflected at the corrugation ends, a standing wave could be formed along the corrugation surface. This corresponds to "axial mode" in BWOs with hollow SWS [9,10]. The effect of axial mode appears as a discrete change in the radiation power when the voltage changes. However, there is no clear discreteness or peak for the cylindrical SP-FEL as shown in Figs. 6 and 7.

In Fig. 9, dispersion curves of our cylindrical system are shown. There is no overlap between cylindrical surface wave (CSW) and waveguide modes of surrounding waveguide (TM_{01}, TM_{02}....). Hence, in the cylindrical SP-FEL, only the cylindrical surface mode can contribute to an axial mode formation. And in this case, axial modes may not be excited clearly as is shown in Figs. 6 and 7. One possible reason is an attenuation of surface wave along the axial direction due to rectangular corrugation. The attenuation impedes the standing wave.

In our experiments, radiations of tens of kW are observed in the voltage region less than about 90 kV. As expected from the dispersion curves in Fig. 2, the intense radiations may be attributed to backward wave oscillation in the negative group velocity region of cylindrical surface wave. Above 90 kV, the radiation decreases or is not observed in our experiments. In this case, radiations may be due to traveling wave interaction in the positive group velocity region. Generally, it is true that the traveling wave interaction is able to lead to an oscillation when an adequate feedback mechanism exists. However, such a feedback may not be expected in our corrugated cylinder. For example, axial modes would play an effective role in the feedback mechanism. However, axial mode effects are not observed clearly as discussed above.

In conclusion, backward wave oscillation based on a cylindrical surface wave of SP-FEL is demonstrated for the first to our knowledge. The cylindrical SP-FEL is composed of a corrugated cylinder and a surrounding hollow waveguide. The surrounding hollow waveguide is used to collect and extract the radiations. Uniformly distributed annular beam is generated by a disk cold cathode in a weakly relativistic region less than 100 kV. The radiation power level of backward wave oscillation based on the cylindrical surface wave is tens of kW in the region of 60-90 kV. The annular beam can carry high currents larger than tens of A and can cover the entire surface of cylindrical corrugation. Hence this cylindrical SP-FEL is suitable to increase power handling capability and is attractive for practical use.

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