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Preliminary Experiment on Smith-Purcell Radiation Based on Cylindrical Surface Wave

円柱表面波を用いたスミス・パーシャル放射の予備的実験

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Smith-Purcell (SP) radiations based on cylindrical surface wave are examined. Cylindrical surface waves are formed on metal cylinders having a periodically corrugated wall. Corrugation parameters are those used in K-band backward wave oscillators (BWOs). The corrugated metal cylinders are excited by an axially injected coaxial annular beam in a weakly relativistic region less than 100 kV. Cylindrical surface wave excitations due to BWO are observed at about 23 GHz. And SP radiations are observed in the higher frequency regions up to about 90 GHz, which is about 4 times higher than the frequency of cylindrical surface wave.

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 [1-4]. Since "super-radiant SP emission" was reported in Ref. [1], 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. When the electron beam passes near the grating surface, a spontaneous SP radiation may be excited. 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. The interaction may result in a backward wave oscillation (BWO) or traveling wave tube (TWT) operation depending on the group velocity of the surface wave. Given the relatively low energy and the intrinsic feedback mechanism, BWO is important for SP-FELs.

The super-radiance has not always been observed. Requirements for the SP radiations based on the backward oscillation have been examined [2, 4]. The electron beam is desirable to be flat and to 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 [3], 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 [5,6]. An idea of SP-FEL incorporating the advantages of cylindrical SWS and BWO seems to be very attractive [7].

In this work, Smith-Purcell (SP) radiation based on cylindrical surface waves is experimentally examined. Cylindrical surface waves are formed by periodic corrugations on cylindrical metal walls. The corrugations have a rectangular shape with parameters used in K-band BWO [6] and are excited by an annular beam in a weakly relativistic region less than 100 kV. The current is much higher as compared to plane SP-FELs. The surface wave excitations due to BWO operation are examined in K-band. And SP radiations are studied above K-band.

2. Cylindrical Corrugation

We use a rectangular corrugation on cylindrical surface. 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 $k_0=2\pi/z_0$. Fig.2 shows the dispersion curves of cylindrical surface wave with R_0=8.4 mm, d=1.5 mm and z_0=3.0 mm. The value of h varies from 0.275 mm to 2.2 mm. According to Floquet's theorem, 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. In our experiments, h is 1.1 mm. Fig.2 shows a corrugated cylinder with 20 periods, which is surrounded by a smooth hollow waveguide in experiments.

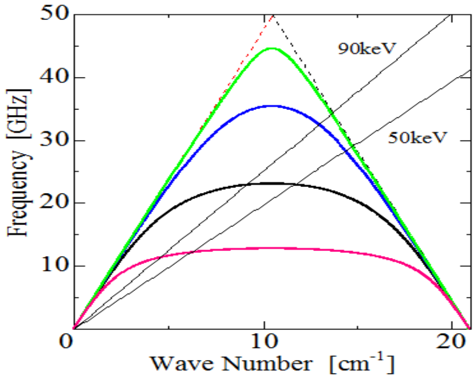

Fig.1. Dispersion curves of cylindrical surface wave for corrugated cylinder with R_0=8.4 mm, d=1.5 mm and z_0=3.0 mm. Values of h are 0.275, 0.55, 1.1 and 2.2 mm, from the top. Beam lines are plotted as a reference. Dotted lines are light lines.

Fig.2. Cylindrical corrugation with both sides propped by supporters.

3. Experimental Results

In order to put the cylinder at the center of the cylindrical system, supports are placed as shown in Fig.1. The left is beam input side and acts as a beam limiter. The limiter's outer and inner radii are φ28 mm and φ19 mm, respectively. And the cylindrical corrugations are excited by an axially injected coaxial annular beam in a weakly relativistic region less than 100 kV. Uniformly distributed annular beam is generated by a novel disk cold cathode in a weakly relativistic region less than 100 kV [6,8]. The current is much higher than that of plane SP-FELs.

Excitations of the cylindrical surface wave by BWO operation are examined by the K-band waveguide detecting system. Based on the time of flight, the frequencies are estimated to be about 23 GHz and well agree with the numerical values of surface wave in Fig.1.

SP radiations are measured and confirmed using U-band waveguide detecting system which has a cut-off frequency of 31 GHz. The surface wave of the corrugation cylinder shown in Fig.2 cannot reach this frequency range.

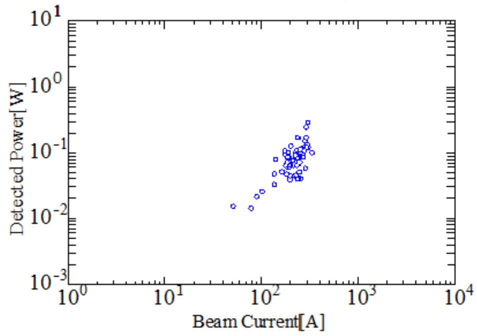

Fig.3. Detected power of U-band waveguide system versus beam current. Output section has a corrugation waveguide with $40z_0$ length.

The power dependence on the current is shown in Fig.3. Beam voltage, current and diameter are 30-100 kV, 80-400 A and about 23 mm, respectively. Although the data dispersion is rather large, the power rises approximately as the square of beam current. As compared to BWO radiations, the slope of log-log plot seems to become gentle. We also detect the radiations for E, F and D band waveguide systems: the cut-off frequency is 31 GHz, 48 GHz, 74 GHz and 91 GHz, respectively. SP radiations are also measured by changing the corrugation length and the output conditions.

4. Summary

SP radiations based on cylindrical surface wave are examined with metal cylinders having a periodically corrugated wall. The cylinders are excited by an annular beam in a weakly relativistic region less than 100 kV. Cylindrical surface waves are excited by BWO operation. And SP radiations in the higher frequency range are observed. SP frequencies reach up to 91 GHz, about 4 times higher than the frequency of cylindrical surface wave. SP radiations depend on the corrugation length and the output conditions.

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