ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-TUPRB035

STIMULATED EMISSION OF THz COHERENT DIFFRACTION RADIATION IN AN OPTICAL CAVITY BY A MULTIBUNCH ELECTRON BEAM*

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Abstract

Accelerator-based terahertz (THz) radiation has been expected to realize a high-power broad-band source. Employing a low-emittance and short-bunch electron beam at a high repetition rate, a scheme to resonantly excite optical cavity modes of THz spectrum range via coherent diffraction radiation has been proposed. The confocal cavity design is the special case that resonance conditions of all the eigen modes coincide, resulting in realizing broad-band excitation. But in general cases of non-confocal cavities, the resonance condition depends on the mode, and the resonance peak becomes wide and weak. We performed an experiment with a non-confocal cavity as a follow-up experiment of that we have done with a confocal cavity. The result confirmed that the confocal design is the key for a broad-band source.

INTRODUCTION

Light sources have played important roles in progress of science in various fields. Since the terahertz (THz) spectrum range is at the gap of conventional technologies, THz source has been most immature in the wide range of spectrum. Accelerator-based THz sources have been developed aiming to realize a useful high power source. At the cERL (compact Energy-Recovery Linac [1]) in KEK, a low-emittance, short-bunch, and high-repetition rate electron beam is available as a superconducting linac test facility. This beam is suitable for performing an experiment of stimulated coherent diffraction radiation. We have been developing a system aiming to develop a high power broad-band THz source. The scheme is explained in Fig. 1. A multi-bunch beam passes through an optical cavity formed by two concave mirrors with a beam aperture in the center. The cavity length, distance between mirrors, is designed so that the fundamental frequency of the optical cavity matches to the bunch repetition rate. A coherent radiation in THz range is emitted when beam passes through the mirror aperture via coherent diffraction radiation (CDR) process. The radiation is stacked in the optical cavity and it interacts with the following bunches as a decelerating electric field. Since the effect enhances the beam-to-radiation conversion of the following bunches, this can be understood as a stimulated radiation. We have performed a proof-of-principle experiment [2]. Similar type of experiments via CTR [3] and CSR [4] have been done also.

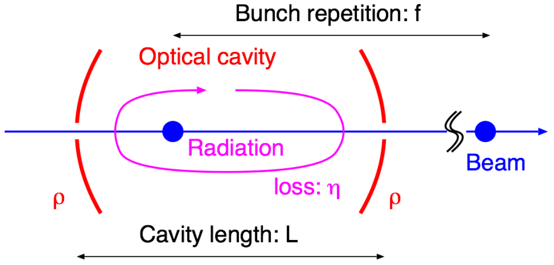

Figure 1: Scheme of the experiment. A multi-bunch beam goes through the aperture of the optical cavity. The radiation emitted in the optical cavity is coherently stacked [2].

In our previous experiment [2, 5], the optical cavity was designed to be confocal by choosing the radius of curvature of the mirrors to be equal to the cavity length. It sets the shift of the carrier-envelope-phase (CEP) in the cavity round-trip to be zero. This is the special condition to realize a broad-band excitation of the cavity. By measuring the THz power while scanning the cavity length, we observed a narrow and strong resonance peak which corresponds excitation of thousands of longitudinal modes at the same time. In order to confirm that the confocal design is the key for the broad-band excitation, we performed a follow-up experiment with a non-confocal cavity by replacing the cavity mirrors with ones of different radius of curvature.

PRINCIPLE

The detail of the principle and calculation procedure is found in elsewhere [5]. The phase shift in the resonance condition for the j-th longitudinal mode, whose frequency is $f \times j$ with f being the fundamental frequency of the cavity, can be written as

$$\Delta\theta^{(j)} = 2\pi \left(j - \frac{4}{\pi} \tan^{-1} \sqrt{\frac{L/\rho}{2 - L/\rho}} \right) , \qquad (1)$$

where ρ is the curvature radius of the mirrors, L is the cavity length.

Figure 2 shows calculation results. It plots the excited THz power, the total power in the spectrum range of 0.26 to 0.65 THz, as a function of the cavity length. Two types of cavity parameters, confocal case and non-confocal case (corresponding to the one of this experiment), are compared. In the confocal case, the resonance condition is at the perfect synchronization, and the peak is narrow and strong. On

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the other hand, in the non-confocal case, the peak position shifts and it becomes wider and weaker. Figure 3 is the cavity length scan of the non-confocal cavity for frequency components of 0.3, 0.5, and 1.0 THz of 10% bandwidth. It shows that the resonance condition shifts with the frequency. This is the reason of the wider and weaker resonance peak of Fig. 2, and broad-band excitation can not be realized by a non-confocal cavity.

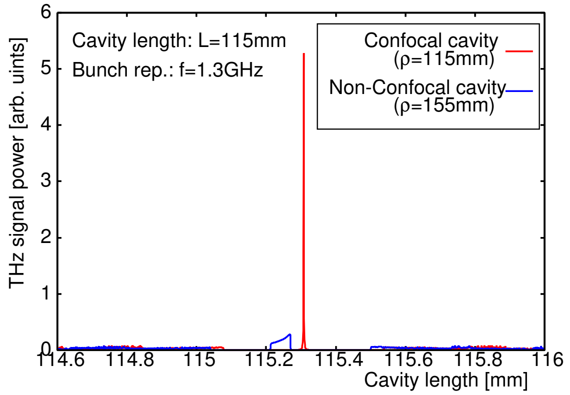

Figure 2: Calculation result of cavity length scan. Excited THz power in wide-band detection is plotted as a function of cavity length. The cavity loss is assumed to be $\eta = 0.01$.

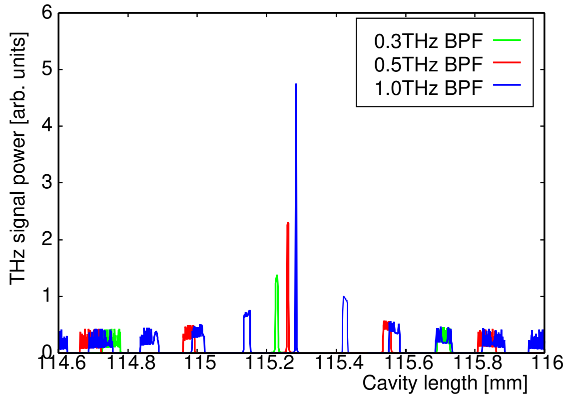

Figure 3: Calculation result of cavity length scan. Assuming inserting band-pass-filters in front of the detector, THz signal of at each frequencies of 0.3, 0.5, and 1.0 THz are plotted as a function of cavity length.

EXPERIMENTAL SETUP

The experimental setup is installed at the straight section of the return loop of the cERL, where a short bunch beam is available in the bunch compression mode (Fig. 4). The detail of the beam line layout and beam tuning procedure are found in elsewhere [5, 6]. The experimental parameters are summarized in Table 1. The bunch repetition of 1.3 GHz corresponds to the fundamental frequency of 115.3 mm cavity length. In our previous experiment performed with the confocal design, the radius of curvature of the mirrors was 115 mm. Whereas in this experiment, it was changed to 155 mm. The other parameters were the same. The experimental setup is shown in Fig. 5. One of the cavity mirrors is mounted on a piezo actuator stage for scanning the cavity length. A fraction of the THz radiation excited in the optical cavity was coupled out through the beam hole and it was extracted to the air in the transverse direction. The radiation power was measured with a liquid-He cooled Si bolometer placed at the focal point. Band-pass-filters (BPF), center frequencies of 0.3, 0.5, 1.0 THz and bandwidth of 10%, could be inserted in front of the bolometer.

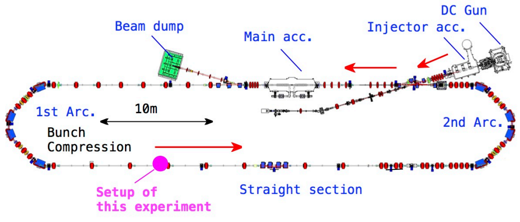

Figure 4: Layout of cERL accelerator. The experimental setup is installed at the straight section of the return loop [5].

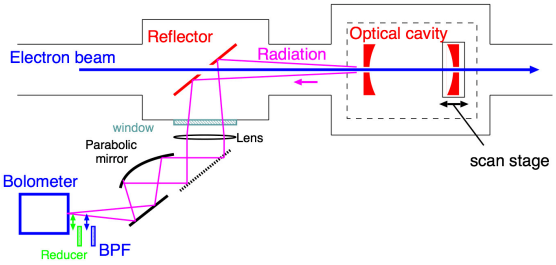

Figure 5: Experimental setup. The THz radiation from the optical cavity is extracted in the air and detected with a bolometer [5].

Table 1: Parameters of the experiment

Cavity parameter	
Cavity length (L)	115 mm
Radius of curvature of mirror (ρ)	155 mm
Diameter of mirror hole	3 mm
Thickness of mirror	10 mm
Diameter of mirror	50 mm
Beam parameter	
Beam energy	17.6 MeV
Bunch repetition	1.3 GHz
Macro-pulse length	1 µs
Macro-pulse repetition	5 Hz
Bunch charge	1.2 pC
Bunch length (rms)	120 fs
Beam size (rms)	240 mm

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RESULT

Figure 6 plots the results of cavity length scan, i.e., the bolometer signal was measured while changing the cavity length by the piezo stage. The data of without BPF case corresponds to the calculation given in Fig. 2. As expected, it shows a wider and weaker resonance peak than that we observed in the case of the confocal cavity (Fig. 7). The width of the peak was measured to be 30 µm (FWHM), whereas it was 150 nm in the confocal cavity case.

Figure 8 plots the results of cavity length scan around the peak with various BPFs in front of the bolometer. It corresponds to the calculation given in Fig. 3. It shows that the peak position shifts with the frequency as expected.

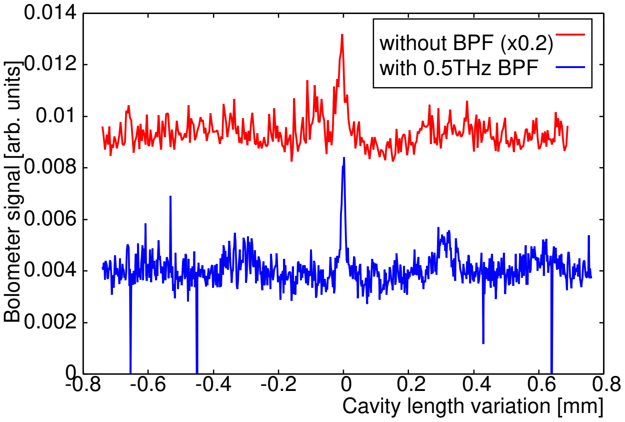

Figure 6: Experimental results of cavity length scans in wide range (non-confocal cavity). The resonance peak turned out to be wider and weaker than our previous experiment with a confocal cavity.

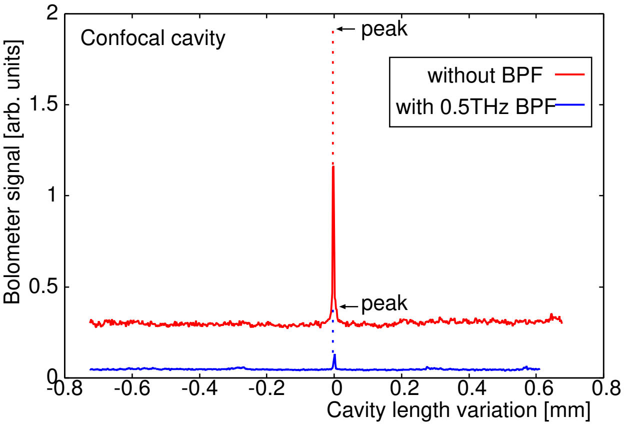

Figure 7: Results of cavity length scan with the confocal cavity obtained in our previous experiment [5]. Note that the peak was too sharp to correctly sample in the rough step used in the wide range scan. The peak heights measured in fine scans are indicated by arrows.

CONCLUSION

We have been developing a THz radiation source via stimulated coherent diffraction radiation. Optical cavity modes of THz spectrum is excited by a multi-bunch electron beam passing through the beam aperture on the cavity mirrors. In order to excite broad spectrum at the same time and realize mode-lock oscillation, the confocal cavity design is essential. In order to confirm the dependence on cavity design, we performed an experiment with a non-confocal cavity. The experimental results showed that the resonance condition shifted with frequency and it resulted in a wider and weaker resonance peak. The results agree with the calculation, and they support the principle given in our previous paper [5].

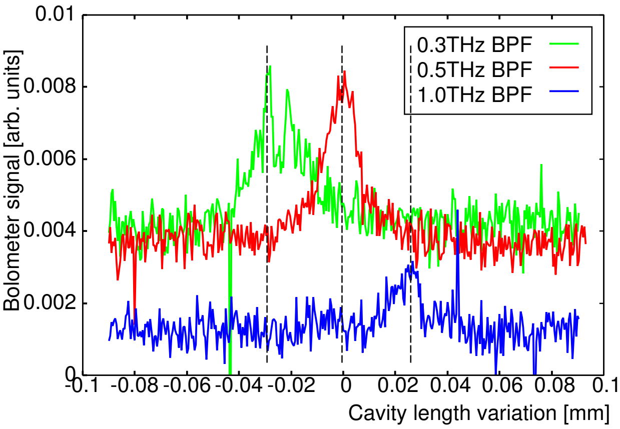

Figure 8: Experimental results of fine cavity length scans around the peak performed with three types of BPFs. The dotted lines indicate expected distances between peaks.

ACKNOWLEDGEMENTS

We would like to thank the cERL development team and CASA (Center for Applied Superconducting Accelerator) of KEK for their support in regard to the beam operation. This work was partially supported by JSPS KAKENHI Grant Number 16H05991 and 18H03473, and by Photon and Quantum Basic Research Coordinated Development Program from the Ministry of Education, Culture, Sports, Science and Technology, Japan. We also thank NEDO for supporting cERL activities.

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