Electromagnetic field enhancement in metallic metamaterials : A potential for compact terahertz free-electron lasers

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***Abstract*—Our recent efforts suggest that there exists strong electromagnetic field enhancement in our recently proposed metallic metamaterial. Of particular importance here is the potential for the realization of compact terahertz free-electron lasers (THz-FELs) using this structure. We present the capability of controlling electromagnetic field enhancement, which must be one of the main issues in developing the compact THz-FELs. Moreover, switching and sensing abilities of this structure could also be investigated for other metal-based THz applications. The numerical and experimental works will be presented in the conference.**

I. Introduction And Background

Metallic metamaterials have been of great interest over the last decades because of their anomalous optical properties [1]. Perfect transmission of light through an array of sub-wavelength aperture [2,3] and guidance of light, acting like a dielectric slab waveguide [4] are the key phenomena below diffraction limit. The physical origin of such behaviors stems from localization of electromagnetic waves in metallic metamaterials. An important fact is the realization of the electromagnetic field confinement in open and sub-wavelength metallic structures.

Utilization of the optical properties of the metallic metamaterials for cathodoluminescence has also been developed such as Smith-Purcell and Cerenkov radiations [5]. These phenomena have been considered as potential applications for compact THz-FELs. Excitation and couple-out of Cerenkov radiation in metallic metamaterials were recently proposed [6,7]. Despite the clear insight into the physical origin, the possibility of distributed feedback mechanism for coherent radiation has not been fully understood yet.

We present our recent progress on the novel approach for compact THz-FELs using metallic metamaterials. It is found that the electromagnetic field enhancement in the modified metallic metamaterial can be controlled by only geometrical factors. Optimizing the quality factor by properly determining geometrical factors, we have observed the potential of this structure for the compact THz-FELs using particle-in-cell codes. The numerical and experimental works will be presented in the conference.

II. Electromagnetic Field Enhancement Using Incoming Electromagnetic Waves

Fig.1(a) depicts a schematic view of the recently proposed metallic metamaterial [7]. In order to calculate the field enhancement, a finite-difference time-domain code is employed. A normal incident *p*-polarized Gaussian pulse, the center frequency of which is about 0.35THz, is injected and the electromagnetic energy confined in the structure is measured in time. The confined energy slowly leaks as time goes on as shown in Fig.1(b) and thus the lifetime and quality factor of the resonances can be measured. Similar phenomena of such field enhancement under subwavelength conditions have been studied theoretically and experimentally [8-10]. This type of structures is known as *metallic compound gratings*. One group added more than one slits and the other group gives different width of slits in a period. The structure depicted in Fig.1(a) appears somewhat different from the others because the additional degree of freedom in electromagnetic distribution is given in the direction normal to the surface. However, the strong field enhancement still exists in the direction parallel to the structure due to localization and damping of the surface states formed by the array of subwavelength slits. Detailed results will be presented in the conference. The experimental setup for observation of the field enhancement is in progress. A vector network analyzer and two double-ridged horn antennas have been prepared for calibration, transmitter and receiver respectively in anechoic chamber.

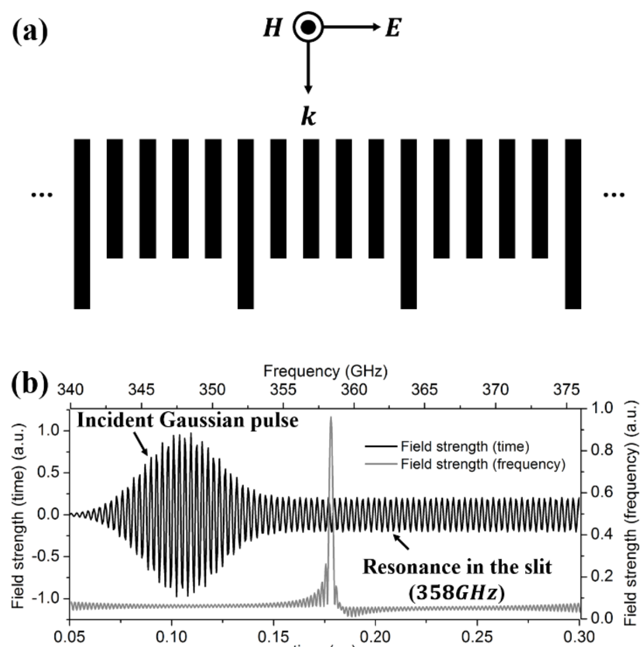

Fig. 1. (a) The schematic view of the metallic metamaterial. (b) Electric field strength within the slit measured in time and frequency, manifesting the excitation of the resonance.

III. Electromagnetic Field Enhancement Using Incoming Free Electrons

Excitation of the resonances using incoming electrons has also been investigated using a particle-in-cell code. Fig. 2 describes Cerenkov modes excited by an infinitely long periodic array of pre-bunched electrons. The frequency of the space-charge mode is fixed and electromagnetic field increasing speed inside the structure is measured for different electron energies as shown in Fig. 2 (a). The inset figure depicts a contour view of electric field in the direction parallel to the surface of the structure, excited by 10KeV electron energy. Out-of-phase between adjacent waveguide resonances in slits contributes to the field enhancement due to extremely low effective dipole moment. As previously discussed, however, such enhanced mode experiences the radiation damping due to the modification. The diffraction radiation angle depends on the velocity of electrons and the period of modification d: $k\cos\theta_n = k_b - 2\pi|n|/d$, where θ_n is the radiation angle measured from a direction parallel to the surface of the gratings with spectral order n, $k_b = \omega/v_e$ is the dispersion of the space-charge mode and v_e is the velocity of electrons.

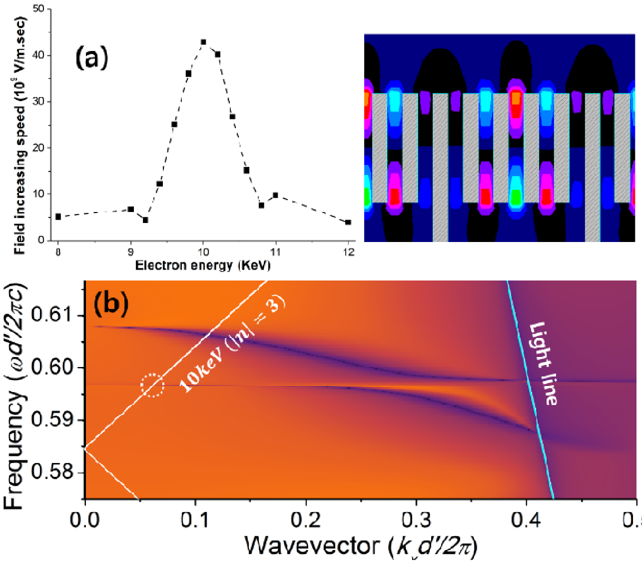

Fig. 2. (a) Left: Field increasing speed within slits with different energies of incoming electrons. Right: contour view of the near-field pattern of electric field component parallel to the structure. (blue for positive and red for negative) (b) Dispersions of the electromagnetic modes of the structure and space-charge mode of electron beam.

IV. Distributed Feedback Mechanism For Coherent Radiation

A single electron bunch passing close to the surface of the structure was considered in the previous studies [6,7]. Instead, a continuous electron beam, current density of which is 50A/cm^2, is injected to the structure in order to observe the distributed feedback process without external sources. The length of the structure in Fig.3 is about 1cm and even much shorter length for coherent electron beam modulation via the enhanced surface states has been observed in particle-in-cell simulation results, suggesting a potential for compact THz free electron lasers using this structure. Such distributed feedback mechanism was experimentally observed for Smith-Purcell radiation by utilization of a scanning electron microscope [11]. This process in Cerenkov radiation with radiation damping, however, has yet been unclear. Moreover, for the practical compact devices, instead of modification of electron microscopic systems, precise fabrication process such as surface roughness and beam-grating alignment are critical in practice.

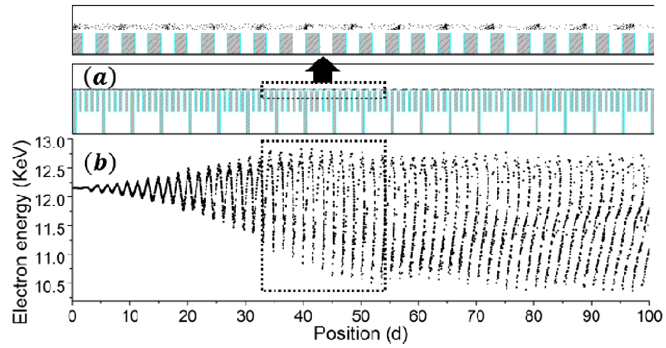

Fig. 3. Snapshots of the phase spaces of the electron beam propagating close to the metallic metamaterial: (a) the spatial distribution of electrons above the structure and (b) the energies of electrons positioned along the structure. The position parameter d is the grating period. Coherent electron beam modulation is manifested.

V. Conclusion

In conclusion, the metallic metamaterials recently shown in the previous studies manifests a potential for compact THz free electron lasers as a beam-wave interaction structure. It is found that the modification of the sub-wavelength grating structure yields radiative damping, which can be geometrically controlled, to the enhanced surface waves. The structure has properties of narrow bandwidth and high-Q under subwavelength condition, suggesting other metal-based THz applications such as optical sensing and switching. The numerical and experimental works will be presented in the conference.

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