High-Order Terahertz Vortex Fields Driven by Free Electron Beam: Phase Modulation in Multi-Helical Structures

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ABSTRACT

Utilizing azimuthally varying slow-wave structures to apply precise spatial phase modulation to electromagnetic waves provides a novel degree of freedom for free-electron vortex radiation. Previous studies have shown that when free electrons pass through a helical superstructure, spatial vortex fields can be effectively excited and manipulated via the Smith-Purcell radiation (SPR) mechanism[1]. By loading a helical superstructure onto a metallic cylindrical shell, the cooperation between an annular electron beam and a multi-helical structure can control the topological charge of the vortex radiation based on its number of grooves and handedness[2]. Furthermore, the Cherenkov wakefield mechanism excited by dielectric-loaded structures has been proven to be an effective approach to enhancing the coherence and frequency selectivity of vortex radiation[3].

This paper presents the latest research progress on the beam-wave interaction between an electron beam and a multi-helical superstructure, with the expectation of reproducing and expanding the generation of vortex radiation fields within a more streamlined architecture by driving multi-filar helices with a circular electron beam. Focusing on the azimuthal phase modulation effect of the multi-helical structure, a dielectric-loaded structure is taken as an example: at the 500 GHz band, when a circular electron beam propagates through a hollow dielectric cylinder (with a wall thickness of 100 μm) loaded with multi-filar metallic helices, the internally excited field is modulated by the helical structure and directly radiates into a free-space vortex field carrying orbital angular momentum.

The angular momentum of this vortex field maps directly to the handedness and the number of strands in the multi-helical structure. Under the condition that the radiation power and operating frequency remain essentially stable, the topological charge of the vortex radiation field can be independently controlled solely by altering the handedness and the number of helices. In this work, both the number of helices and the topological charge are increased to 4, which has been verified by simulations, successfully and stably converting the internally excited fields into a spatially uniform, high-order multi-mode vortex radiation.

To fully reveal the performance and potential of the helical structure, based on the streamlined architecture where a circular electron beam directly drives the metallic helices, this paper also conducts performance comparison and optimization regarding core parameters such as the number of helices, duty cycle, and pitch, further clarifying the modulation characteristics of the multi-helical structure. This work expands the spatial radiation dimension of free-electron-induced terahertz waves, providing a highly promising multi-mode radiation source scheme for future terahertz communications and high-resolution imaging.

References

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