Multifunctional THz Vacuum Electronic Sources Enabled by Momentum Engineering and Symmetry-Broken Microstructures

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ABSTRACT

The Terahertz frequency range, situated between the microwave and infrared regions, has long been identified as a frontier for next-generation technological breakthroughs [1]. However, the development of compact, high-power, and spectrally agile THz sources remains a significant challenge, often referred to as the "THz Gap." While solid-state devices face inherent thermal and power density limitations at higher frequencies, vacuum electronic devices (VEDs) have re-emerged as a premier solution. This is due to their exceptional power-handling capabilities, vacuum-based low-loss transport, and high scalability of interaction circuits from millimeter to micron scales [2]. This work presents significant progress in the development of multifunctional THz vacuum electronic sources by leveraging subwavelength periodic microstructures and advanced beam-wave interaction physics.

Central to this research is the utilization of free electrons to excite Cherenkov radiation within customized electromagnetic environments. By employing the principles of momentum engineering, we integrate spoof surface plasmons (SSPs) and sophisticated grating architectures to bridge the momentum mismatch between slow moving electrons and fast electromagnetic waves. This approach allows for the precise alignment of the electron beam's slow-wave space charge line with specific Floquet–Bloch harmonics. Such deterministic control enables the design of devices with unprecedented functional flexibility. We demonstrate tunable far-field directivity, allowing for dynamic beam steering without mechanical movement, and wideband polarization synthesis, which is critical for complex communication and imaging environments. Furthermore, we report the generation of broadband tunable vortex beams carrying defined orbital angular momentum (OAM), offering a new dimension for high-capacity THz multiplexing. A key highlight of this work is the proposal of a novel, all-electric THz frequency comb concept. Unlike traditional combs that rely on complex optical pumping or mode-locked lasers, our design exploits symmetry-broken quasi-bound states in the continuum (quasi-BICs). By strategically introducing structural asymmetries into the periodic micro-resonators, we transform non-radiating dark modes into leaky resonances with extremely high-quality factors. The resulting extreme near-field enhancement facilitates intense electron-wave interaction, producing a stable, comb-like spectrum directly from an electron beam. This mechanism provides a pathway toward high-precision THz metrology and molecular spectroscopy in a compact vacuum-sealed package.

In conclusion, by emphasizing the microscale control of electron-wave interactions through dispersion tailoring and topological physics, this work establishes a new design paradigm for THz VEDs. The integration of momentum engineering and BIC-inspired architectures paves the way for a new generation of multifunctional, compact THz sources. These advancements hold transformative potential for high-resolution radar, cognitive electronic warfare, and advanced spectroscopic sensing, ensuring that vacuum electronics remain at the heart of the THz revolution.

References

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