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Editorial

High-Frequency Vacuum Electron Devices

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Vacuum electron devices at frequencies of millimeter waves and terahertz play highly important roles in the modern high-data rate and broadband communication system, high-resolution detection and imaging, medical diagnostics, magnetically confined nuclear fusion, etc. For the fast motion velocity of electrons in the vacuum medium, they have the advantages of high power and high efficiency, as well as compactness, compared with other present radiation sources, such as solid-state devices.

We established the Special Issue of "High-Frequency Vacuum Electron Devices" with the aim of enhancing the exchange of research information on the theory, design, simulation, processes, and development of these devices to promote their applications, and to attract young researchers and engineers starting out in this important field, which is still vital on the basis of modern electronic science and information technology.

There are many kinds of vacuum electronic RF power devices, including linear-beam devices, cross-field devices, and fast-wave devices. At high frequencies up to terahertz, klystrons, TWTs, BWOs, and gyrotrons are widely studied either for their high power, or for their broad instant or tuning bandwidth. In order to obtain high-quality performances at millimeter wave and terahertz frequencies, novel technologies and processes have emerged in the past decade, including microfabrication using MEMS and 3D printing, new diamond-related materials for windows and attenuators. At the same time, new slow-wave structures and resonant structures have also been studied, such as meta-structures, high-order mode operation and sheet electron beams, which are used to obtain high power; spurious depression; and the mitigation of manufacturing difficulties, specifically in high-frequency regimes. Revolutionary technologies in the components and parts of the devices, including cathodes, electron guns, I/O structures, magnetic focusing systems, and collectors, have played critical roles in the development of high-frequency vacuum electron devices.

This Special Issue consists of fifteen papers covering a broad range of topics related to the design, simulation, manufacturing, and testing of high-frequency vacuum devices with a wide range of frequencies up to 340 GHz, and devices including gyrotrons, TWTs, and EIKs, together with beam-forming and confining cathodes, slow-wave structures, and mode converters, etc.

High-frequency gyrotrons are core devices for Dynamic Nuclear Polarization Nuclear Magnetic Resonation (DNP-NMR) applications to significantly improve the sensitivity and resolution of high-field NMR in medical systems and scientific research. In [1], entitled "Linearly Polarized High-Purity Gaussian Beam Shaping and Coupling for 330 GHz/500 MHz DNP-NMR Application", from Beijing University, the design and calculation of a corrugated TE11-HE11 mode converter and a three-port directional coupler for a 330 GHz/500 MHz DNP-NMR system are proposed. The output mode of the mode converter presents a highly linear polarization of 98.8% at 330 GHz for subsequent low loss transmission. Gyrotron-TWTs have the advantages of high power and a broad bandwidth at a millimeter wave frequency band for long-distance accurate detection and high-resolution imaging. In [2] of this issue of "Design of a Dual-Mode Input Structure for K/Ka-Band Gyrotron TWT", the structure for the input coupling, which is composed of two different types of input couplers, with the coaxial input coupler for the Ka-band $TE_{2,1}$ mode and the Y-type input coupler for the K-band $TE_{1,1}$ mode, is described. The designed dual-mode input coupler has the advantages of a broad bandwidth and low loss and can be used effectively in dual-band Gyro-TWTs.

TWTs are widely investigated at high frequencies for their advantages of a high bandwidth, high power, and compactness for applications in high-date rate communication and high-resolution imaging. In this issue, there are eight papers dealing with the research and development of TWTs with novel integrated slow-wave structures (SWSs) and meander-line structures, as well as whole tubes. Three papers focus on meander-line SWSs but with varied supporting structures and materials. One paper [3] is based on the design of multiple Dielectric-Supported Ridge-Loaded Rhombus-Shaped Wideband Meander-Line Slow-Wave Structures for a V-Band TWT; the simulations show that the structure has a larger bandwidth, higher gain, more stable structure, and better heat dissipation ability. For high-power TWTs with meander-line SWSs, a staggered-ring micro-strip line (SRML) structure [4] is proposed and designed in the paper of "Broadband-Printed Traveling-Wave Tube Based on a Staggered Rings Micro-strip Line Slow-Wave Structure", and the input and output structures with micro-strip probes and transition sections are also shown. The particle-in-cell (PIC) simulation results indicate that the SRML TWT has a maximum output of 322 W at 32.5 GHz under a beam voltage of 9.7 kV and a beam current of 380 mA, and the output power is over 100 W in the frequency range of 27 GHz to 38 GHz.

Two new methods for the analysis of meander-line SWSs are presented in the issue. As we know, machine learning (ML) and deep learning (DL) are widely investigated and applied in many fields, while in one paper [5] in this Special Issue, ML and DL are introduced in the design of vacuum devices, where exact numerical simulation data are used in the training as a form of supervised learning to obtain the geometric dimensions. They are also used for the design of D-band meander-line TWTs with 160 GHz central frequency. Another paper [6] proposes a new method for solving the dyadic Green's functions (DGF) and scalar Green's functions (SGF) of multi-layered plane media, in which the DGF and SGF are considered to be suitable for arbitrary boundary conditions and for the electromagnetic analysis of complicated structures, including meander-line SWSs.

For other novel SWSs for millimeter wave structures, a cosine-vane folded waveguide [7] is used for a miniaturized E-Band TWT for wireless communication, and an over-moded flat-roofed sine waveguide is designed for high-power multi-beam TWTs. The E-band TWT has the properties of 9 W with a low voltage of 9 kV and compactness; this investigation is performed by the team from BVERI. For the higher frequency of 340 GHz, a flat-roofed sine waveguide [8] with over-mode operation and multiple electron beams is designed, and the PIC simulation results show that 50 w power can be obtained with a −3 dB bandwidth of 13 GHz.

Sheet electron beams used in vacuum devices can significantly increase the output power; there are two papers in this issue focusing on beam forming and transport, which is critical for the success of the whole tubes. In one paper [9], a periodic cusped magnet (PCM) is used for the design and evaluation of a G-Band TWT. A high beam-current density of 285 A/cm^2 and a voltage of 24.5 kV are successfully verified through a beamstick tube with over 81% transmission and a distance of 37.5 mm, which has compactness and light-weight beneficial properties. In another paper [10], a new electron beam method is proposed using both a periodic magnetic field and an electrostatic field (PM-E), which has the ability to resist the influence of the assembly error in the practical tubes, and the electric field can be conveniently changed to correct the deflection of the beam trajectory.

The integration of tubes for phase array systems has the advantages of high power and high efficiency. One paper [11] in this issue proposes the design of a Ka band using double parallel-connecting micro-strip meander-line SWSs, realizing power output through 2×2 ports. For each output port of one channel, the simulation results reveal that the output power can reach a high power of 566 W and a broad −3 dB bandwidth of 7 GHz.

Klystrons often have a higher power, higher gain and higher efficiency than TWTs, which is addressed two papers in this issue. One paper [12] performs an investigation of the high efficiency of a coaxial multi-beam relativistic klystron. PIC simulation is used to analyze the beam–wave interaction physical process and optimize the high-frequency parameters. The calculation shows that the klystron with 14 electron beams and a 4.2 kA bam current can deliver 1.02 GW power and 48.7% efficiency at 500 kV beam voltage. Another paper [13] is based on the G-Band klystron, which operates in high-order mode and in klystron TM31 mode, and a barbell six-gap cavity is selected. The interaction calculation shows that there is no risk of mode competition resulting from the big mode separation, and the power of 650 W with a 3 dB-bandwidth of 700 MHz can be obtained at 16.5 kV voltage and 0.5 A beam current.

Processing is critical for practical devices, ref. [14] of this special issue supplies a new structure for the assembly of the meander line SWS, in which an attenuator is employed to support the meander line on the bottom of the enclosure rather than welding them together on the sides. The three-dimension Particle-in-cell (PIC) simulation results show that with a 4.4-kV, 200-mA sheet electron beam, a maximum output power of 126 W is obtained at 38 GHz with electronic efficiency of 14.3%.

Finally, one of the most promising fields in vacuum electronics is the combination of microelectronics and modern 2D materials for high-performance electron emission sources and transistors. One paper [15] is based on vacuum transistors using carbon nanotubes (CNT) as electron sources. In the vacuum triode, multi-walled CNTs are used, with the principle of field-assisted thermal emission, which is fabricated using microfabrication technologies and has the advantages of improving the stability and uniformity of the devices. The experiment shows that the CNT transistor exhibits an ON/OFF current ratio as high as 104, and the surface of the emitters shows much lower gas molecule absorption than cold field emitters.

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