Guest Editorial
Introduction to the Third Special Issue on High-Power Microwave Generation

I. Introduction

RESEARCH on the generation of high-power microwave and millimeter-wave radiation has been pursued at government, university, and industrial laboratories for about the last two decades. The rapid growth of the field has resulted from the possible applications of these sources in such areas as the RF heating of fusion plasmas, advanced particle-accelerator systems, plasma and solid-state diagnostics, materials processing, high-power radar systems, electronic warfare, and directed energy concepts. Many of these studies were prompted initially by the availability in the early 1970's of high-power pulse-line accelerators capable of producing intense, relativistic electron beams to drive the RF structures. At the present time, a wide variety of beam-production methods are employed, ranging from pulse-line accelerators driving field-emission cathodes to high-power pulse modulators driving thermionic or photo-cathodes. Whatever the driver, new microwave source concepts and improvements in the design of conventional microwave tubes have led to a steady increase in both the peak power and operating efficiency of these sources at wavelengths ranging from 30 cm to 1 mm. In fact, the maximum reported product P/λ^2 (peak microwave power divided by the wavelength squared) has increased by an order of magnitude each decade since 1970.

This is the third Special Issue of the IEEE Transactions on Plasma Science on high-power microwave generation. The first Special Issue on the topic was published in December 1985 and contained 27 papers covering a broad range of sources in the frequency range of 3 to 200 GHz. The second Special Issue was published in April 1988 and contained 29 papers covering an even broader range of devices and operating characteristics. This issue, reflecting the rapid increase of activity in the field, contains 43 papers submitted by researchers from all over the world.

The papers in this Special Issue have been organized into four general categories: (i) Fast Wave Devices (including free-electron lasers and electron-cyclotron masers); (ii) Slow Wave Devices (including backward-wave oscillators, traveling wave tubes, Cherenkov masers, klystrons, and magnetrons); (iii) Plasma Devices (including the virtual cathode oscillator); and (iv) a category comprising papers not easily identified with the previous three categories, such as the Magnicon.

II. Fast Wave Devices

This class of devices is characterized by a transfer of energy from an electron beam to a propagating electromagnetic wave with a phase velocity greater than or equal to the velocity of light. Electron-cyclotron masers (or gyrotrons), for example, are designed to produce radiation at frequencies near the electron-cyclotron frequency or one of its harmonics by the resonant interaction of a beam-cyclotron mode with one of the modes of the conducting boundary system. This interaction is driven by the electron-cyclotron maser instability or, in the case of large orbit devices, by the equivalent negative mass instability.

This Special Issue contains 12 papers covering various aspects of gyrotron research. This section begins with an invited paper by Levush and Antonsen on mode competition and control in high-power gyrotron oscillators. This work is significant in that the cavity size in gyrotrons is typically much larger than a wavelength, and mode competition can be a critical problem. In addition, Dumbrajs *et al.* have reported the theoretical treatment of mode competiton in a gyrotron with a nonfixed axial RF field profile for arbitrary cyclotron harmonics. Theoretical work has also been reported by Davies *et al.* on absolute and convective cyclotron-resonance maser instabilities, by Latham on ac space-charge effects on gyroklystron amplifiers, and by Manheimer *et al.* on the equilibrium and stability of quasi-optical gyrotrons. Numerical simulations of multimode simulations of the quasi-optical gyrotron are reported by Riyopoulos.

A number of experimental studies of electron-cyclotron masers in various configurations are also included. Experimental results from a high-power quasi-optical gyrotron are reported by Fliflet *et al.*, and Park *et al.* have reported results from a *Ka*-band gyrotron backward-wave oscillator experiment. Spira-Hakkarainen *et al.* have reported results from a submillimeter-wave harmonic gyrotron experiment, and Guo *et al.* discuss a complex cavity gyrotron for harmonic operation. Large-orbit gyrotron experiments in which the electron orbits typically encircle the axis of the system are also well represented in this Special Issue. Furuno *et al.* have reported on the operation of a large orbit, high-harmonic gyrotron traveling-wave tube amplifier, and Kou *et al.* report on studies of prebunched high harmonic gyrotrons.

Free electron lasers (FEL's) are a second class of fast-wave devices described in this Special Issue. In FEL's, a

0093-3813/90/0600-0257$01.00

beam of relativistic electrons is induced to radiate coherently by injecting the beam through a periodic transverse-wiggler magnetic field. Because the output wavelength of a typical free-electron laser scales as $\lambda = \lambda_w/2\gamma^2$, where λ_w is the wiggler period and γ is the relativistic mass factor for the electrons, they are prime candidates for the production of coherent radiation at very high frequencies. Interest in FEL research remains high, and a total of 11 papers on this topic appear herein.

Although high-frequency operation in FEL's has primarily been obtained by use of high-energy electron beams, papers by Stoner *et al.* and Booske *et al.* report studies of novel FEL configurations employing very small period wigglers to achieve a high operating frequency with more modest electron energy requirements. FEL theory papers include work by Botton and Ron on the two-stream instability in FEL's, studies by Fruchtman on wave profile modification in an FEL with and without a waveguide, theoretical work on the interaction of high- and low-frequency waves in an FEL by Latham and Levush, studies of a 280-GHz FEL amplifier with waveguide, space-charge, and tapered magnetic field effects by Chang *et al.*, a paper by Sternbach on the coupled wave theory of FEL sidebands in a waveguide, and studies of the plasma effects on FEL's by Tripathi and Liu.

FEL experiments have been reported by Boehmer *et al.*, who describe a long-pulse free-electron maser experiment, by Kehs *et al.*, who report experiments in which a powerful electromagnetic wave is used in place of the magnetostatic wiggler, and by Dodd and Marshall on studies of spiking radiation in the Columbia FEL experiment.

III. Slow Wave Devices

This second class of devices typically employs a dielectric or slow wave structure to support electromagnetic waves with phase velocities less than the velocity of light. Included in this category are traveling-wave tubes and backward-wave oscillators, Cherenkov masers, klystrons, and magnetrons.

Because they typically employ linearly streaming electron beams and slow wave structures constructed either from a periodic metal grating or a dielectric, research on traveling-wave tubes, backward-wave oscillators, and Cherenkov masers is closely related. A total of nine papers are included on these devices. The section begins with an invited paper by Bugaev *et al.* describing Soviet experiments on relativistic multiwave Cherenkov generators employing two-separate slow wave structures. These devices have produced an astonishing 15 GW of RF at 10 GHz and 3.5 GW at 45 GHz, both results almost an order of magnitude greater than previously obtained in any device. A second paper by Bugaev *et al.* explores the capabilities of millimeter wave sources of this type. Shiffler *et al.* have reported experimental studies of a high-power traveling wave tube amplifier, and Morey and Birdsall report on a new numerical code for the simulation of TWT's. Backward-wave oscillator studies reported include the experimental studies of plasma-filled BWO's by Carmel *et al.*, and related theory by Minami *et al.* Studies of the dependence of the BWO operation on the effective beam gamma are reported by Butler *et al.* Experimental research on high-power Cherenkov masers, in which the slow wave structure is replaced by a dielectric, is described in the paper by Main *et al.*, and theoretical work by Kho and Lin is presented on cyclotron–Cherenkov and Cherenkov instabilities.

An important development in the field of high-power microwave generation in recent years has been the studies at the Naval Research Laboratory of relativistic klystron amplifiers driven by modulated, intense, relativistic electron beams. These studies are summarized in an invited paper by Lau *et al.* In the experimental work reported in this paper, 3 GW of RF was observed at a frequency of 1.3 GHz at an efficiency of 35% and a 37-dB gain. Theoretical and numerical studies of the operation of these devices and the effects of their intense-beam space charge are also summarized in this paper.

Because of their relatively high output power and efficiency and because microwave output is easily obtained in the desirable TE_{10} rectangular waveguide mode, relativistic magnetrons continue to be the focus of considerable research activity. A total of five papers describe ongoing relativistic magnetron research efforts. Theoretical papers include the report by Chen on the theoretical studies of magnetron phase-locking efforts at the Massachusetts Institute of Technology, and numerical simulations of relativistic magnetrons by Weatherall. Experimental studies include the studies of a high-repetition-rate magnetron reported by Phelps, the temporal studies of long-pulse magnetron operation by Treado *et al.*, and studies of lightweight, high-repetition-rate, portable magnetron research and development by Spang *et al.*

IV. Plasma Devices

The virtual cathode oscillator, or vircator, is one of the most prominent in this class of microwave sources. In this device, an intense electron beam is injected into a cavity at a current which is considerably in excess of the space-charge limit, and oscillations of the resulting virtual cathode can be coupled to an appropriate cavity mode, resulting in the production of coherent radiation. The largest experiment in this class, the reflex diode experiment on the Aurora facility at the Harry Diamond Laboratories, is described in a paper by Huttlin *et al.* In addition, results of phase-stability studies of a magnetron-driven vircator experiment are reported by Price and Sze. Finally, Davis *et al.* report on studies of the enhanced efficiency from a new, related device designed to improve on vircator efficiency and radiation line width, the Reditron oscillator.

V. Other Devices

In addition to the papers detailed above, several other microwave-generation concepts are currently under study. Numerical studies of a cyclic beam buncher are reported by Peratt *et al.*, and a conceptual design of a high-power

Magnicon, a concept originally proposed in the Soviet Union, is reported by Manheimer. In this device a linear electron beam is passed through a special RF cavity and made to precess in the azimuthal direction. The beam is then injected into an extraction cavity in which the electrons continuously lose energy to the wave, resulting in a very high operating efficiency.

VI. Conclusions

It is evident from both the number of submissions to this Special Issue and the range of topics covered that research on high-power microwave sources is flourishing. More importantly, it is clear that a significant improvement in the performance of high-power microwave sources has resulted from this research, as indicated by almost any measure of performance. Much additional work, however, remains. High harmonic operation of these devices will require extensive theoretical study to find a way of suppressing mode competition. Experimentally, high harmonic operation will require even higher quality electron beams than have been generated to date. Relativistic beam-plasma sources, in which a fill plasma is used to decrease the beam space-charge effects and even to enhance beam–wave interactions, are a largely new field of study with potentially rich rewards. The mating of these high-power sources to high-repetition-rate power supplies of a more manageable size is clearly needed in many cases, and many of these sources do not operate at high power for pulse durations in excess of 100 ns regardless of the electrical-input duration. Furthermore, electron-energy recovery schemes can be exploited in many of these devices to obtain an increased efficiency, if needed. Finally, the advent of vacuum microelectronic field-emitting diodes may also have a significant impact on future high-power diode designs.

In summary, much has been accomplished and much remains to be done. The richness of the field is in large measure a product of the willingness of researchers to employ new technology to exploit old ideas, and old technology to exploit new ideas.

Acknowledgment

The guest editors are very grateful to the more than 100 reviewers who carefully read the manuscripts submitted for this Special Issue. They also wish to express their appreciation to N. Swader and B. Aycock for their careful handling of all the clerical duties associated with the issue.

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