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High-Power Microwaves at 25 Years: The Current State of Development

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Abstract

The field of high-power microwaves (HPM) has matured considerably in the 25 years since the initial development of relativistic backward wave oscillators (BWOs) by researchers from the Institute of Applied Physics and the Lebedev Institute in Russia [1] and from Cornell University in the US [2,3]. In this paper, we review some of the signs of the maturity of the field, including changes such as an observed narrowing in the number of source types under development, an increase in commercial suppliers, and a growing internationalization of the research field. In addition, within the context of historical developments in the field, we discuss the development of high peak power systems and the apparent abandonment of the pursuit of ever-higher power in favor of the development of gigawatt-level systems with manageable weight and volume, repetitive operation, and tunability.

Introduction

This year is the 25th anniversary of the publication of the first paper providing experimental results for a true, high-power microwave source [1]. In the paper, researchers from the Institute of Applied Physics in Nizhny Novgorod and the Lebedev Institute in Moscow described a relativistic BWO producing 400 MW in 10-ns output pulses. A year later, workers at Cornell University, following up on Nation's discovery of low-efficiency microwave emission in electron beam experiments [2], produced a somewhat higher power in a similar device [3]. Since that time, power levels of a gigawatt or more have been generated with a wide variety of sources, some relativistic versions of conventional devices such as the magnetron, and others with operating features unique to the field of HPM, such as the vircator. These power levels have been generated at frequencies ranging from about 1 GHz to deep into the millimeter-wave range at 140 GHz. Power levels have approached, and in a few instances, surpassed 10 GW, and the scaling to even higher power levels has been considered in several cases.

On this 25th anniversary, signs of maturity can now be recognized in the field. They can be found in changes in the composition of the field, in terms of the participants, the sources under investigation and the applications driving their development, and in the geographic diversity of interest. Signs of maturity can be found also in the research agenda for the field. Two trends stand out in particular. First, we perceive a trend toward the production and use of versatile gigawatt- or near-gigawatt-level systems with manageable weights and volumes, repetitive operation, and frequency-tunable output. Second, we note the community-wide pursuit of longer pulses with microwave output tracking the power pulse of the electron beam driving the source. This latter work is summarized very succinctly in the proceedings of last summer's International Workshop on High Power Microwave Generation and Pulse Shortening, held in Edinburgh [4]. In this paper, we'll outline the changes we see in the field and review the trends we perceive in the development of versatile high-power systems.

Changes in the field of HPM

We see three notable signs that point to the growing maturity of the field of HPM: the narrowing of the types of sources under active development and the applications that drive that development; an increase in the number of commercial suppliers of HPM systems; and a growing internationalization of the research field. With regard to the focus in source development, we note that three types of sources are becoming increasingly popular among users and researchers, in part because each has strong commercial support: relativistic magnetrons, high-power BWOs and TWTs, and reltrons and super-reltrons. Two other sources also continue to attract significant interest: the magnetically-insulated line oscillator (MILO), attractive because it offers power levels now reaching 1 GW in a low-impedance source without the complexity and bulk of an applied magnetic field; and the low-impedance relativistic klystron amplifier (RKA), another low-impedance source that has generated power levels around the 10-GW mark with pulse energies of about 1 kJ.

In addition to these sources, broadly attractive to researchers interested in high-peak power applications, we also see focused efforts driven by two well-defined applications:

- RF linacs for TeV electron colliders -- klystrons, based both on upgraded conventional tube technology and on relativistic source technology; magnicons; gyroklystrons; and TWTs.
- ECRH heating of fusion plasmas -- gyrotrons and, notably, the FEL under development by the FOM Institute in the Netherlands.

The application for RF linacs requires sources producing power in the 100-MW range at frequencies between about 10 and 30 GHz. On the other hand, the plasma heating application requires high average power in a continuous mode at frequencies in the range of 150 GHz and above. Strictly speaking, this latter is not an HPM regime, but the requirement for high-average power at these high frequencies stresses the state of the art.

In contrast to the aforementioned sources, we see a number of types falling by the wayside. Most notably, perhaps, is the virtual cathode oscillator, or vircator. This source offers high power levels in a relatively simple, low-impedance configuration that doesn't require an applied magnetic field. Unfortunately, vircators tend to up-chirp in frequency, due to gap closure in the electron beam diode, and they suffer from poor efficiency in many cases. The virtode, invented in Ukraine, offers some solutions, but to date it hasn't been widely pursued. Another factor contributing to the vircator's lack of popularity is the fact that magnetrons and reltrons offer attractive alternatives at the frequencies of interest. Relativistic gyrotrons and cyclotron autoresonance masers, which originally promised high peak power at higher frequencies, also seem to have fallen out of favor, although, as metioned earlier, high average power gyrotrons still enjoy favor in their niche. The reasons for the lack of popularity here can perhaps be traced to reduced interest in high peak power sources at high frequencies, particularly at the expense of high operating voltages. Finally, the high-peak-power free electron laser (FEL) has fallen out of favor. While this source can be made to operate over a wide frequency range, the complexity of the required wiggler magnets, the high-voltage needed for high-frequency operation, and the guiding magnetic field additionally needed for high-power operation at lower frequencies perhaps result in a source of undesired complexity.

A sure sign of maturity in the field is the growing number of commercial suppliers for HPM systems. US firms find that the HPM hardware market in the 1990s mostly lies abroad due to diminished US-government purchases. We estimate total hardware revenue of about $4M per year. Industrial research and development in the US, however, has steadily declined in the 1990s and is about zero now due to low profit margins. The smallness of this business makes larger defense firms reluctant to enter the field.

Current exporters of HPM equipment -- sources and pulsed power -- in the US are Titan Corp. (reltrons, systems) and Maxwell Physics International (relativistic magnetrons, vircators, complete turnkey systems). Integrated Technologies and Kiser Research distribute Russian equipment (BWOs, orotrons, RADANs, systems) around the world, as do the Russian institutes, notably the Institutes of Applied Physics, Electrophysics, and High-Current Electronics, themselves. Thomson Shorts has entered the European market, which is currently dominated by American firms.

Overall, the internationalization of HPM research can be traced to an interest in HPM as possibly a key emerging defense technology of the 21st century. The early programs in the USSR and US have evolved and influenced other countries to take an interest. The collapse of the USSR led to the dispersal of some Russian and Ukrainian HPM workers and the eagerness of others to collaborate in international programs. At the current time, we would divide the various national efforts as follows:

- Major programs -- US and Russia;
- Medium-scale programs -- UK, France, China, and Ukraine; and
- Emerging programs -- Sweden, Germany, Israel, Taiwan, India, and Australia.

Depending on the scale of the effort in each country, work can be found at government laboratories, industrial firms, and in the universities.

Development of versatile HPM systems

The trend toward the development of versatile HPM systems is particularly interesting when viewed in historical context. We point to four significant programs in the development of HPM sources:

- Vircator experiments conducted on the AURORA accelerator at the Harry Diamond Laboratories (circa 1986-1991). AURORA was an enormous radiation effects simulator, and one arm of this four-arm accelerator, producing an approximately 7-MW, 160-kA beam, was used for HPM experiments. The cathode and drift-tube diameters in these experiments were 53 and 122 cm, and the A-K gap was varied up to 35 cm. At this large size, frequencies varied from about 0.7-1.0 GHz. Peak power levels of 1-4 GW were extracted from each of 18 ports, and a total pulse energy of about 1 kJ was generated. Unfortunately, the power was highly variable during a pulse, and the frequency was also highly variable from shot to shot.
- The Naval Research Laboratory RKA experiments (circa 1985-1996). This source operated at low-impedance and utilized near-virtual-cathode formation to very effectively bunch electrons in an amplifier configuration. Power levels of 6 GW could be generated reliably in 140-ns pulses at 1.3 GHz, giving pulse energies approaching 1 kJ. Single shots at levels up to 15 GW were seen at times. Further increases in power were expected to require a triaxial configuration, in which a high-current electron beam was propagated in a coaxial drift tube in order to raise the space-charge limiting current of the device, although this source never came to full realization.
- The Lawrence Livermore and Lawrence Berkeley National Laboratories high-peak-power FEL (circa 1982-1995). These experiments demonstrated gigawatt production at high-efficiency using wiggler tapering on the ETA-1 accelerator. Later experiments on the upgraded ETA-2 accelerator produced gigawatt-level output at 140 GHz, as well as high average power in 2-kHz bursts using magnetic switching technology. Ultimately, this experiment was terminated when it was deemed that the technology was overly complex, in contrast to high average power gyrotrons, for ECRH heating of fusion plasmas, the application for which it was ultimately funded.
- The multiwave Cerenkov generator (MWCG) and relativistic diffraction generator (RDG) experiments conducted on the GAMMA accelerator at the Institute of High-Current Electronics. The long-pulse accelerator, operating in flat pulses to one microsecond, was used to drive sources producing power levels approaching 10 GW in X-band, and gigawatt power levels at frequencies of 30-40 GHz. Pulse energies of the order of 1 kJ were generated, and a variety of pulse shortening mechanisms were examined. Ultimately, scaling experiments showed the way to operation at high ratios of the diameter of the source to the output wavelength. Unfortunately, this scaling also pointed to a requirement for extremely large capacitor banks to drive the field coils producing the guide field in the interaction region.

In common, each of these significant experiments was very large. In the case of the RKA and the MWCG/RDG systems, scaling experiments pointed the way to power levels potentially in the tens to hundreds of GW, but the sizes and complexity of these systems became daunting. In the case of the FEL, size and complexity once again became problematic, particularly in regard to alternatives for the ultimate application.

Today, we point to three systems enjoying widespread popularity among researchers and users because of their high output power, of the order of a gigawatt, their manageable size and weight, their tunability, and their demonstrated capability for repetitive operation. In addition, each is essentially available from a commercial supplier:

- Relativistic magnetrons, produced by Maxwell Physics International, generating power in the gigawatt range and pulse energies of about 100 J, at frequencies in the L- and S-bands;
- BWOs and TWTs, produced at the Institute of High-Current Electronics, producing power levels up to and beyond a gigawatt and energies of 100 J or more, depending on the size of the pulsed power unit, primarily in the X-band; and
- Reltrons and super-reltrons, built by Titan in Albuquerque, NM, with power levels approaching a gigawatt and energies of 200 J and more, primarily in the L- and S-bands, with scaling to higher frequencies at lower power.

The relativistic magnetrons, when powered by a compact linear induction accelerator (CLIA), also developed at Maxwell Physics International on the model of a system developed at the Institute of Nuclear Physics at the Tomsk Polytechnic Institute, have utilized magnetic switching technology to operate at kilohertz rates. Using an in-house developed technique, they have also been shown to have a tuning range at high power of about 30% in S-band. These systems are also widely used in pulse-lengthening research and in the development of coherently-phased arrrays of HPM sources.

The BWOs, driven by IHCE SINUS pulsed power generators, can also operate at repetition rates of 100 Hz. These X-band machines have been the drivers for experiments in the development of high-efficiency BWOs that can be mechanically tuned over about a 5% bandwidth while operating at constant power using control systems developed at the University of New Mexico.

The reltrons and super-reltrons are, in themselves, quite compact, their size being determined almost solely by the pulsed power systems driving them. They've become workhorses in simulation and effects studies, and tunable output is available using a variety of different modulating cavities, as well as different extraction cavities operating at harmonics of the modulation frequency.

Summary

The field of HPM is maturing in its 25th year. Years of investigation have led to a sharpening of the research focus, created a commercial supplier base, and generated international interest in the technology. While earlier experiments have demonstrated very high power levels over a broad range of frequencies, users and the research community have fixed on several systems with very versatile features and relatively compact dimensions. Nevertheless, research continues on several other sources with attractive prospects. Looking into the future, the prospects for the near term appear to favor sources aimed at defense interests, with linear accelerators and ECRH plasma heating constituting additional technology drivers.

References

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