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Introduction

This new edition of *High Power Microwaves* is a substantial departure from the 1992 first edition.[1] That work was a technical monograph that reflected the activities and trends up to that time. High power microwaves (HPM) has moved from being a promising technology to implementation in several applications. HPM systems are being built, studied, and applied not only in the U.S., Russia, and Western European countries such as the U.K., France, Germany, and Sweden, but also in China and developing nations such as India, Taiwan, and South Korea.

In this new volume, we have adopted a *systems point of view.* A significant change in the HPM community has been increasing emphasis on optimizing the entire system. It is widely realized in the HPM community that only by viewing HPM systems as integrated devices may the output of sources exceed present levels of power and pulse energy. Further, the community of potential HPM users demands it. One can no longer separate the system into discreet constituent components and optimize them separately. In adopting a systems point of view, one begins with a basic understanding of the constraints imposed by the application. Then one identifies subsystem component classes and how they interact and properly takes account of the requirements of ancillary equipment.

To get the flavor of this new approach, we advise the reader to begin by reading two chapters before reading the specific technical chapters that follow. Chapter 2, on HPM systems, describes how to conceptualize an HPM system by making choices of components based on a standard methodology. Chapter 3, on HPM applications, sets out the requirements for such systems.

Another major difference between the two editions is that this edition is a textbook intended to be used by students in HPM courses or for self-study by the technically trained. Therefore, we have introduced problems for most of the chapters. (Readers who wish to acquire solutions for these problems, or additional problems, should contact the authors at http://home.earthlink.net/~jbenford/index.html.)

There are several other innovations:

- An HPM formulary giving rules of thumb that the authors have found useful
- A new chapter on ultrawideband systems

1.1 Origins of High Power Microwaves

HPM has emerged in recent years as a new technology allowing new applications and offering innovative approaches to existing applications. A mix of sources that either push conventional microwave device physics in new directions or employ altogether new interaction mechanisms has driven the quantum leap in microwave power levels. HPM generation taps the enormous power and energy reservoirs of modern intense relativistic electron beam technology. Therefore, it runs counter to the trend in conventional microwave electronics toward miniaturization, with solid-state devices intrinsically limited in their peak power capability.

Our definition of HPM is:

- Devices that exceed 100 MW in peak power
- Devices that span the centimeter- and millimeter-wave range of frequencies between 1 and 300 GHz

This definition is arbitrary and does not cleanly divide HPM and conventional microwave devices, which have, in the case of klystrons, exceeded 100 MW. The HPM devices we consider here have reached powers as high as 15 GW.

HPM is the result of the confluence of several historical trends, as shown in Figure 1.1. Microwaves were first generated artificially by Hertz in the 1880s. Radio came into use at lower frequencies in the early 20th century with the advent of gridded tubes. In the 1930s, several investigators realized that higher frequencies could be obtained by using resonant cavities connected to electrical circuits, and the first cavity device, the klystron, was produced in 1937. This was followed by a burst of activity during the Second World War that included the extrapolation of the magnetron and the invention of the traveling wave tube (TWT) and the backward wave oscillator (BWO). Modulators that frequently used gridded power tubes powered all these sources. In the 1960s, the cross-field amplifier was developed. Thereafter, the 1970s saw the strong emergence of lower-power, but extremely compact, solid-state–based microwave sources. By this time, microwave tube technology was oriented toward volume production, and the research effort was curtailed.

In the 1950s, efforts to control thermonuclear fusion for energy production led to a detailed understanding of the interaction between particles and waves, and ultimately to the requirement for new tube developments using gyrotrons for higher average power at frequencies that have climbed to over 100 GHz. In the 1960s, electrical technology was extended with the introduction of *pulsed power*, leading to the production of charged particle beams with currents in excess of 10 kA at voltages of 1 MV and more. These intense beams were applied to the simulation of nuclear weapons' effects,

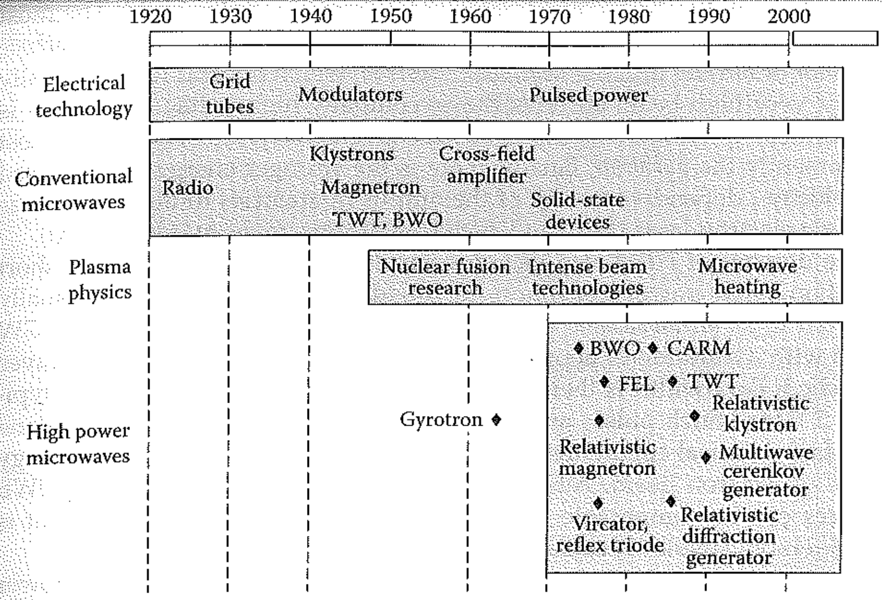

FIGURE 1.1
Historical origins and emergence of high power microwaves.

inertial confinement fusion, and other studies of high-energy density physics. The availability of intense relativistic electron beams was the last piece in the puzzle, allowing the knowledge of wave–particle interaction gained in the study of plasma physics to be put to use in the generation of microwaves. As a consequence of this genealogy, the culture of the HPM community lies closer to those of the plasma physics and pulsed power communities than to that of the conventional microwave tubes. One result of this is that the HPM technology was initially slow to adopt materials and surface and vacuum techniques that are well established in the microwave tube community and essential to resolving the pulse-shortening challenge that HPM faces.

1.2 High Power Microwave Operating Regimes

The first HPM sources were descendants of conventional microwave sources such as the magnetron, the backward wave oscillator, and the traveling wave tube. In these devices, increased power comes from using higher operating currents and stronger beam–field couplings within the interaction region.

Using high voltages to produce so-called relativistic electron beams, meaning electron energies comparable to or greater than the 510-keV rest energy of an electron, has had several profound consequences for HPM. The most important is the introduction of new devices, such as the *virtual cathode oscillator* or *vircator* and the *relativistic klystron*, which depend fundamentally on the very high beam currents that accompany high voltages. Another is the further exploitation to devices based explicitly on relativistic effects, most prominently the *gyrotron*. Finally, there is the stronger energy-, as opposed to velocity-, dependent tuning of the output frequencies in devices such as the free-electron laser (FEL) and cyclotron autoresonant maser (CARM).

The domain of HPM also includes *impulse sources*, which are very short duration, high power generators of broad bandwidth radiation. Usually referred to as *ultrawideband* (UWB) devices, they typically generate ≈1 GW or so with a duration of about 1 nsec, and only a few cycles of microwaves launched. Bandwidth is therefore of the same order as the frequency, typically 1 GHz.[2] Such pulses are generated by direct excitation of an antenna by a fast electrical circuit, instead of the earlier method of extracting energy from an electron beam. Although the peak output power levels of UWB sources can be comparable to narrowband sources, the energy content is considerably smaller because of very short pulse lengths.

The heroic age of HPM, until the 1990s, had the character of a "power derby," during which enormous strides were made in the production of high power levels at increasingly higher frequencies. Researchers in the former Soviet Union/Russia achieved their world-record successes using a series of new devices — the multiwave Cerenkov and diffraction generators and the relativistic diffraction generator (multiwave Cerenkov generator (MWCG), multiwave diffraction generator (MWDG), and relativistic diffraction generator (RDG) — based on large interaction regions many microwave wavelengths in diameter. In the U.S., relativistic magnetrons and klystrons at lower frequencies and FELs at higher frequencies generated the high powers. A measure of the success of these efforts is the product of the peak microwave power and the square of the frequency, Pf^2. Figure 1.2 shows the general history of the development of microwave sources in terms of this factor. Conventional microwave devices (tubes) made three orders of magnitude progress between 1940 and about 1970, but thereafter only minor improvements were made. Conventional devices, the klystron in particular, continue to make advances, albeit slowly. HPM devices began at $Pf^2 \sim 1$ and have progressed upward an additional three orders of magnitude in the ensuing 20 years. The device with the highest figure of merit produced to date is the FEL, with a radiated output power of 2 GW at 140 GHz.

Figure 1.3 shows the peak power generated by a representative sample of high power sources as a function of the frequency. It appears that peak power of many sources falls off roughly as f^2 at high frequencies; however, no clear trend emerges for the lower frequencies below 10 GHz. Why Pf^2? The roughly Pf^2 scaling for a given source type reflects the fact that power extracted from resonant cavity devices is proportional to their cross section, which scales with wavelength squared. In addition, the power in a waveguide, which has a cross section proportional to λ^2, is limited by a

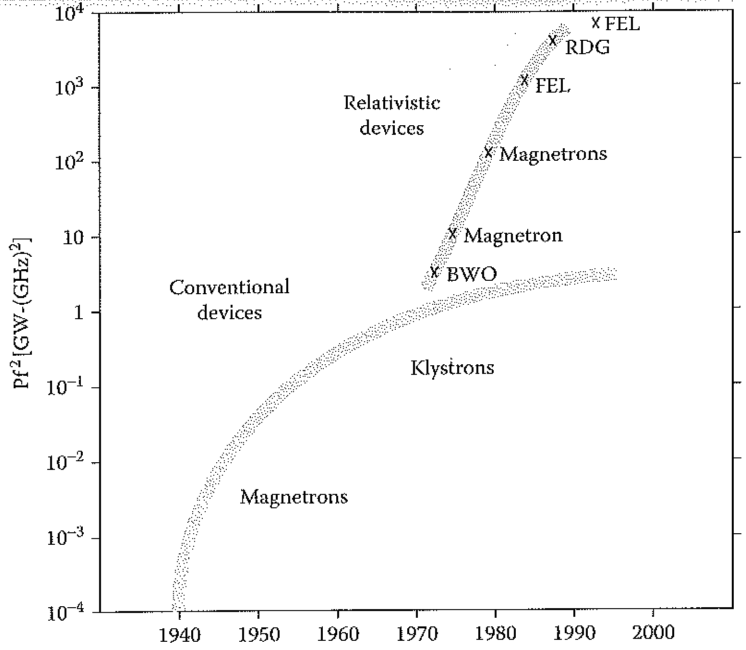

FIGURE 1.2
Growth of microwave devices in terms of quality factor Pf^2.

breakdown electric field. Another meaning is that power density on the target of a microwave beam transmitted is proportional to Pf^2 for a fixed antenna aperture (because antenna gain is ~f^2; see Chapter 5), so it is a good parameter to rank sources for directed energy and power beaming over a distance.

The early heroic age of HPM ended in the 1990s with a sobering realization that devices were fundamentally limited above a peak power of ~10 GW and pulse energy of 1 kJ. These parameters were achieved through considerable effort and the added benefit of sophisticated three-dimensional computational modeling tools that were not available earlier. The term *pulse shortening* came into vogue, encompassing the various causes for the decrease in pulse length as peak power increases, with radiated energy staying roughly constant as power climbed. This has led to a reassessment of the way the HPM community has been developing its sources, as well as a concentration on improving them. Since then, much of the focus has been on improving existing sources: better surface cleanliness and vacuum environment, cathodes that can deliver the requisite electron current densities at low electric fields yet yield minimal plasma, and better designs to ensure that the intense electron beam impacts as little of the electrodynamic structure as possible as it gives up its kinetic energy and passes into the collector. There has been a significant decline in research on new source configurations.

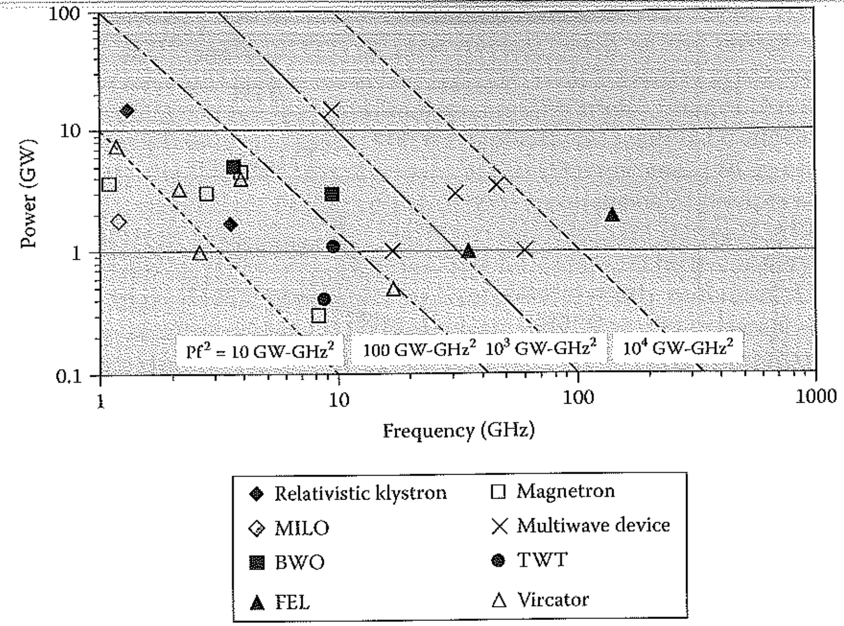

FIGURE 1.3
Peak powers of types of pulsed HPM sources. Values of quality factor Pf^2 vary over several orders of magnitude.

The ultimate limits on HPM source peak power are not well known. They are set by trade-offs between the usual factors that limit conventional tubes, breakdown, and mode competition, and factors unique to HPM, such as intense beam–field interactions and evolution of plasmas from surfaces and diodes. Electrical pulses with power up to about 10 TW are available from a single pulse generator, and one can buy 1-TW generators (a laboratory-based device, not suitable for mobile applications) for a few million dollars, commercially. At a moderate extraction efficiency of 10%, one could therefore expect a peak power of 100 GW. We expect that such powers can be achieved, but only if there is a need for the power and a willingness to accept the accompanying size and cost. To do so requires substantial improvement in understanding the limitations of specific devices and overcoming pulse shortening and source-specific problems such as spurious mode generation.

Another set of issues limits HPM average power achieved in repetitive operation. The convention in HPM has been to quote device efficiency in terms of the *peak power efficiency* of the source, defined as the ratio of the peak microwave power to the electron beam power at that moment. This is to be compared with the *energy efficiency,* which would be the ratio of the microwave pulse energy to the electron beam pulse energy. Aggressive research programs aimed at gaining a detailed understanding of large-signal behavior have been rewarded in certain cases with instantaneous power efficiencies of 40 to 50%; under most circumstances, however, power effi-

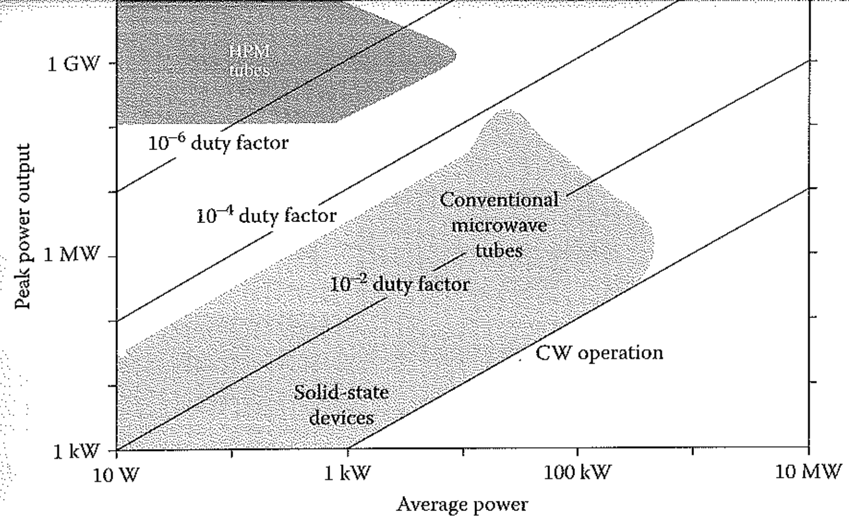

FIGURE 1.4
Peak vs. average power for microwave sources with duty factors.

ciency is in the vicinity of 10%. Energy efficiencies are usually much lower, due to the device falling out of resonance and pulse shortening at high power levels. Therefore, energy efficiencies are seldom quoted in the literature.

A comparison of the peak and average power characteristics for conventional and HPM sources is given in Figure 1.4. The peak power of a device is plotted against its average power. While conventional devices span an enormous range in this parameter space, the HPM devices have not been developed to produce substantial average power levels. This is because conventional sources have been developed to be the workhorses for specific applications, such as radar and particle acceleration, while the HPM sources have not, as yet. The Stanford Linear Accelerator Center (SLAC) klystrons are the highest power devices of conventional origin (~100 MW peak, 10 kW average). The relativistic magnetron is the highest average power HPM device (1 GW peak, 6 kW average). The *duty factor* for HPM sources — the product of the pulse length and the pulse repetition rate — is of the order of 10^{-6} (at most 10^{-5}), whereas for conventional devices it varies from 1 (continuous operation, called continuous wave, CW) to about 10^{-4}. We expect that the impetus provided by HPM applications will spur advances in repetitive operation, and average powers will approach 100 kW. There are as yet no applications for *both* high peak and high average power.

Another comparison of conventional and HPM sources is shown in Figure 1.5. Considering only pulsed devices, i.e., leaving out continuous operation, the conventional tubes typically produce ~1 MW for ~1 μsec, giving a joule per pulse. Klystrons for accelerators produce energetic pulses at 1 to 10 MW. The SLAC klystron has developed to 67 MW, 3.5 μsec, yielding 235 J. This borders on our definition of HPM (>100 MW). HPM sources produced tens

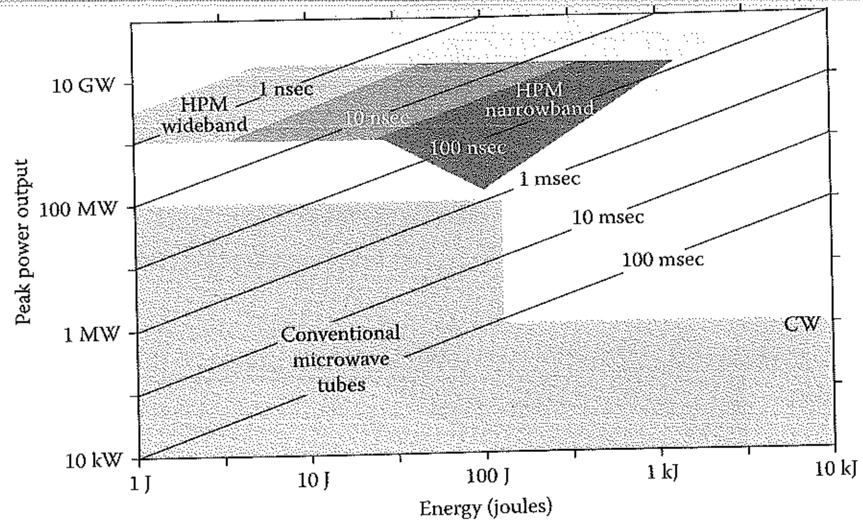

FIGURE 1.5
Peak power and energy from continuous and pulsed (durations shown) microwave sources, narrowband and wideband.

of joules in the 1970s, hundreds of joules in the 1980s, and surpassed a kilojoule in the 1990s (MWCG and relativistic klystron amplifier [RKA]). These developments were achieved by increasing peak power at ~100-nsec pulse duration. Further increasing pulse duration, the obvious route to higher energies, faces pulse shortening.

Most of the devices shown in Figure 1.5 are narrow bandwidth. The wideband impulse sources, with very short pulse durations, fall in the region of 100 MW, <1 J.

The increasing use of HPM sources will also raise the issues of reliability and lifetime. With HPM sources predominantly functioning in a research environment to date, important reliability and lifetime issues have received very little attention. For example, the $>10^{-6}$ Torr vacuum levels of most HPM experiments contrast with the $<10^{-7}$ Torr levels of conventional tubes, where higher pressures are known to cause lifetime problems. Still farther in the future lie the sophisticated issues of bandwidth, gain, linearity, phase and amplitude stability, and noise levels. These can be quite important in the context of a specific application.

The parameter spaces of the current applications of HPM are shown in Figure 1.6. The power levels for directed energy and short-pulse radar vary widely. The highest power requirements are for earth-to-space power beaming (earth-to-space, space-to-space, and space-to-earth, primarily average power driven) and directed energy weapons. It is notable that first-generation HPM weapons approaching deployment are high in average power, operating continuously, not as a series of pulses in a burst (see Section 3.2.3). These are confined mostly to the frequency regime below 10 GHz, in part by atmospheric absorption. Linear colliders (particle accelerators) require higher frequencies (~30 GHz) at about 100 MW. Electron cyclotron resonance heating of plasmas is a much higher frequency application (over 100 GHz), with a continuous or average power requirement of up to 10 MW. Some of these applications are approaching maturity, as described in Chapter 3.

The most stressful applications are military, because military platforms have severe requirements for onboard volumes and masses. Historically, the most comprehensive HPM weapons research programs were in the U.S. and Russia, especially during the Cold War era. There are now significant activities in Europe, with the U.K., France, Sweden, and Germany the most prominent. In Asia, China and India have weapons programs. In Japan, interest is centered on gyrotrons for plasma heating, klystrons for accelerators, and FELs for a broad range of applications that span the frequency spectrum. The Chinese are also investigating gyrotrons, including some innovative configurations, and FELs at laboratories in, for example, Chengdu, Beijing, and Shanghai. To accelerate its program, China has purchased HPM technology from Russia.

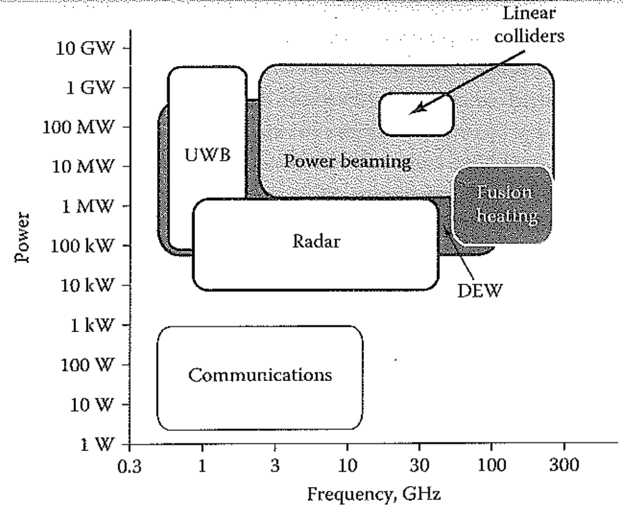

FIGURE 1.6
Domains of HPM applications. "Power" is typically peak power, but in some cases, such as fusion heating and some directed energy weapons (DEWs), it is average power. Regions are schematic; specific schemes vary widely.

1.3 Future Directions in High Power Microwaves

The field of HPM is maturing. Decades of investigation have led to a sharpening of the research focus, created a commercial supplier base, and gener-