Chapter 1 INTRODUCTION

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1.1 SETTING AND MOTIVATION

This book is meant to serve as a definitive reference book for all individuals interested in High-Power Microwave (HPM) sources for possible future military applications. It does not discuss full military HPM systems concepts, nor does it cover specific military HPM applications. Security classification restrictions would obviously not permit such discussions in the open literature. Nevertheless, our military HPM focus, combined with the rich bibliographic references provided for each chapter, make this book important and unique.

Our target audience consists of technically savvy professionals whose interests encompass the emerging technologies of the defense arena. Readers who seek a basic HPM textbook are referred to the forthcoming second edition of *High Power Microwaves* by Benford, Swegle, and Schamiloglu [1]. In fact, the detailed explanations found therein will be invaluable for HPM-novice readers of this book. Furthermore, readers whose interests only extend to U.S. Department of Energy (US-DoE) concerns (e.g., particle accelerators and the heating of fusion plasmas) would be better served by such works as *High Power Microwaves* edited by Granatstein and Alexeff [2], or conference proceedings such as *High Energy Density Microwaves* edited by Phillips [3].

An important distinction that sets this book (and the entire HPM-MURI Program described in the Preface) apart from past HPM studies is its careful integration of knowledge and experience from the commercial vacuum electronics community. We believe strongly that the military HPM community should embrace the proven experience and knowledge of established microwave tube engineering. The "rapid prototyping" environment of HPM's formative years argued against the expensive and time-consuming methodologies used by the tube manufacturers. Now, however, as increased emphasis is placed on converting mature HPM device concepts into fieldable, practical, reliable systems, logic dictates increased attention to proven microwave design and fabrication practices. Throughout this book references are made to engineering techniques that are well documented [4]–[6] and that should form an integral part of the technical libraries of groups who are active in the HPM arena.

1.2 HIGH-POWER MICROWAVES

High-Power Microwaves (HPM) is an imprecise term used by several communities studying the generation of coherent electromagnetic radiation spanning the frequency range of approximately 1 GHz to over 100 GHz. One interpretation of the term is *high-average-power microwaves*, which implies long-pulse duration, high-repetition rate or continuous beam (referred to as "cw") sources. Another interpretation is *high-peak-power microwaves*, which implies short-pulse duration, a low-repetition rate, or "single-shot" sources. Researchers in the former Soviet Union used the term *Relativistic High-Frequency Electronics* to describe this discipline.

The high-average-power microwave sources of today are exemplified by devices such as the Stanford Linear Accelerator Center's (SLAC) S-Band Klystron, which has demonstrated the generation of 150 MW at 3 GHz. This device has gradually evolved over the past six decades from the original works of Hansen, the Heils, and the Varian brothers. (See [7] for a review of the development of the klystron.) The community that the klystron and similar devices belong to can be referred to as the "conventional tube" or "vacuum electronics" community. It is primarily an electrical engineering community. This community employs very disciplined time-proven techniques for engineering their microwave sources. They have design rules and conditioning techniques that can almost be categorized as lore. The strict adherence to their engineering guidelines, coupled with advances in both materials and calculational techniques, have led to the gradual advances in the outputs of their devices that we have witnessed to date. This community seeks to produce reliable, working microwave sources in response to specific customer requirements. Typical government clients of this community's technology would include the U.S. Department of Energy (DoE) for accelerator and plasma heating applications, and the U.S. National Aeronautics and Space Administration (NASA) for communications. Much of the prior HPM literature has been biased toward the high-average-power community.

The high-peak-power but shorter pulse-length microwave sources of today are exemplified by devices such as the Magnetically Insulated Line Oscillator (MILO) [8] at the Air Force Research Laboratory/Phillips Research Site at Kirtland Air Force Base, New Mexico. The MILO has demonstrated the generation of 2 GW at 1.2 GHz with pulse length under 200 ns. This device was first proposed in 1987, but the community from which it originates dates back to the pioneering work of Nation at Cornell University in 1970 [9], and Kovalev and colleagues at the Lebedev Institute in the Soviet Union in 1973 [10]. The community that developed the MILO, as well as the intense beam-driven relativistic cousins of the conventional tubes, is primarily the plasma physics community. Interest among plasma physicists in coherent sources of electromagnetic radiation was spawned by several developments. One was the detailed experimental and theoretical understanding of the interaction between charged particles and electromagnetic waves that was gained as part of the magnetic confinement fusion programs in the 1950s. Another is the development of pulsed power as a major field in the late 1960s, an enabling technology that grew out of the development of sources for radiography. Pulsed power technology provided the ability to generate intense relativistic electron beams, high-perveance[1] beams that provided the possibility of generating high instantaneous power levels of coherent electromagnetic radiation. A further development was the availability of sophisticated particle-in-cell computer simulation tools, coupled with increasingly powerful computers that provided the sophistication required to analyze intense beam-driven sources. Finally, the increasing interest in developing directed energy weapons was the catalyst that hastened the join-

[1] Perveance is defined as the ratio $I/V^{3/2}$ where I is the electron beam current and V is the beam voltage.

ing of these various factors, resulting in research programs focused on high instantaneous power microwave sources.

This book primarily addresses the interests of the latter of those two communities, although the vacuum electronics community shares many of those same interests. It presents the state-of-the-art in the evolution of high instantaneous power microwave sources that has been achieved through a program that has merged the talents of universities, DoD laboratories, as well as industry in the United States. Following the convention of Benford and Swegle [11], we invoke the term High-Power Microwaves (HPM) to denote sources producing coherent electromagnetic radiation from 1 GHz to over 100 GHz with an instantaneous power of at least 100 MW. Figure 1.1 presents a comparison of the peak- and average-power characteristics for conventional and high-power microwave sources.

As discussed in the Preface, this book is not intended to be a comprehensive treatise describing all classes of HPM sources. Rather, the intent is to describe the advances in the field that have occurred primarily under the auspices of an Air Force Office of Scientific Research-administered Department of Defense Multidisciplinary University Research Initiative (MURI). Its five-year duration and U.S. \$15M funding level made it the largest single HPM basic research program in history and endowed it with a breadth and depth of activities that marked it as a watershed. The reader is referred to earlier books and articles that are referenced in the chapters for a more complete discussion of HPM sources.

There is another interesting evolution of military HPM research and development (R&D) activities that is carefully reflected in this book. This involves the increasing military (and commercial) interest in "moderate" power (on the order of 100 kW) *higher frequency* microwave sources. The internal length scales of such devices generally shrink with the increasing frequency of the radiation to be produced. Therefore, for a given operating voltage, the electric field stresses encountered in such devices can easily reach values similar to those found in GW-level, lower frequency HPM sources. This

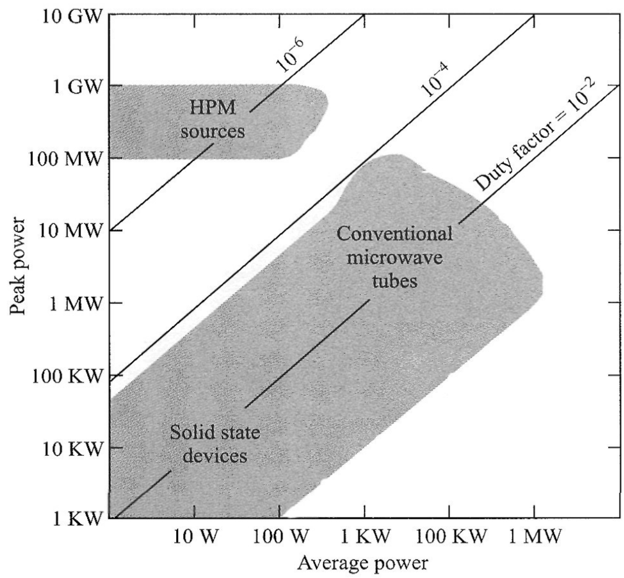

Figure 1.1 Peak power *vs.* average-power domains for microwave production.

results in a general commonality of physics and engineering concerns between those two classes of devices. For that reason, discussions of high-frequency, sub-MW-level device concepts are purposely included in this book.

Researchers working in the higher frequency regimes refer to the so-called quality factor Pf^2, where P is the output power in GW and f is the frequency in GHz. Figure 1.2 illustrates the technical progress made over the past decades in achieving greater quality factors for various device concepts. This evolution is crucial to the success of a number of 94 GHz military systems that will be emerging in the near future.

1.3 ORGANIZATION AND SCOPE OF THE BOOK

In order to best describe the organization of the book, we first present an overview of a generic HPM system in terms of its components, as sketched in Figure 1.3. This book focuses on the three system elements comprising the Microwave Source section depicted in the figure diagram.

Each chapter adheres to a "background/obstacles/future works" sequence in its presentation. Each begins with an historical perspective of the given topical area. Highlights are presented that accurately present the state-of-the-art. Then the major remaining scientific challenges are discussed. Finally, avenues for future progress are described if such opportunities are perceived by the respective chapter contributors.

Chapter 2 provides the motivation for interest in HPM from a U.S. Department of Defense perspective. The scope of this chapter is much broader than that of this book so that HPM research can be presented in the broad context of DoD interest in microwave sources for a variety of applications.

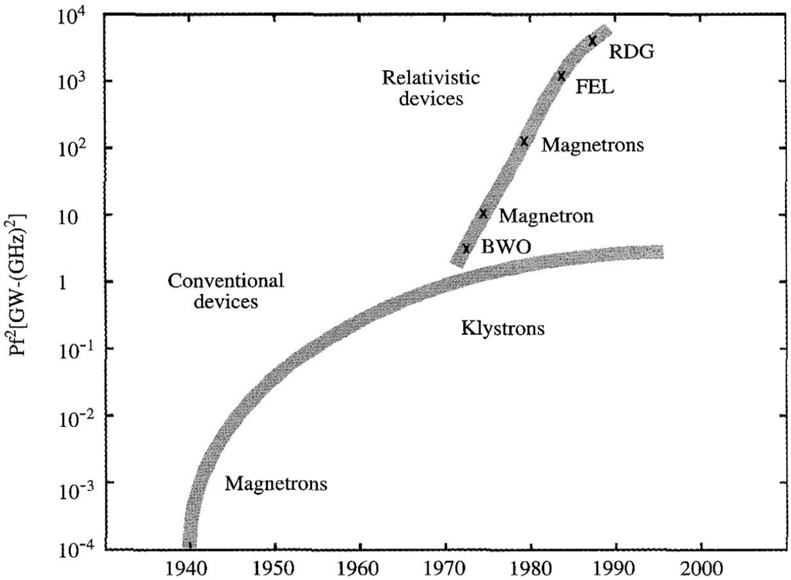

Figure 1.2 Evolution of microwave devices in terms of the quality factor Pf^2. BWO = backward wave ocsillator, FEL = free electron laser, and RDG = relativistic diffraction generator (the latter two sources are not discussed in this book).

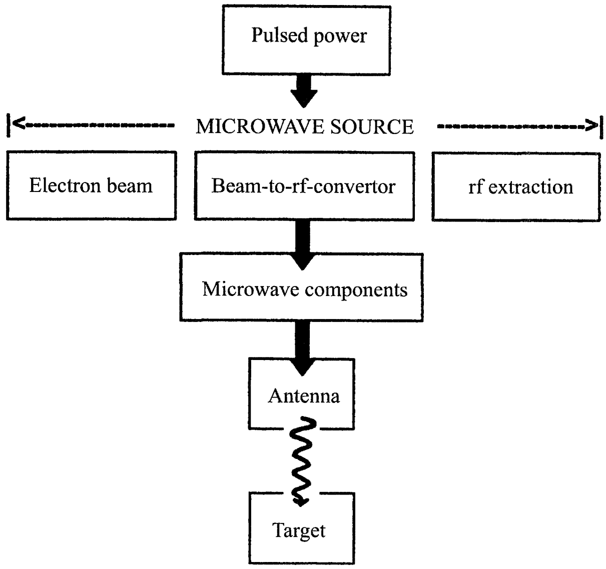

Figure 1.3 Block diagram of an HPM system.

Chapters 3–6 review HPM device concepts that have been studied and developed in the context of the coordinated research program discussed in the Preface. Chapter 3 presents information on the sources that have been generating the highest instantaneous powers to date in this research program. Chapter 4 discusses the *pulse-shortening* phenomenon. The editors decided to group this chapter with the source chapters since, whereas Chapter 3 presents the "good news" (outstanding achievements in terms of high-power levels generated, greater insight gained into the understanding of source physics), Chapter 4 presents the "bad news" (greater powers generated but energy per pulse remains fairly constant). The remaining two HPM-device chapters then review advances in Čerenkov devices (Chapter 5) and Gyrotron Oscillators and Amplifiers (Chapter 6).

Chapters 7–11 discuss so-called enabling technologies for HPM sources. In this regard, much of the information in these chapters can be considered as having one of two purposes: either mitigating the pulse-shortening problem discussed in Chapter 4 and/or making HPM more practical from a systems standpoint. Chapter 7 discusses advances in the use of plasma prefill in HPM sources to beneficially affect device operation. Such a plasma fill can provide broad frequency agility, enhance microwave generation efficiency, and decrease guide magnetic field requirements. Chapter 8 reviews advances that are on the way to making HPM more practical. The advent of a "Smart Tube" HPM source is discussed, in addition to other strategies for controlling the radiation generation process in these devices. Chapter 9 discusses advances in cathodes that can lead to increases in emitted current densities while minimizing the problem of plasma formation. The broader view of electron guns for a wide spectrum of sources is also presented. Chapter 10 reviews advances in the theoretical understanding of multipactor and other phenomena associated with window and radio frequency (rf) breakdown. It also discusses novel materials that are being developed for mitigating breakdown. Finally, Chapter 11 reviews advances in computer modeling and simulation techniques that have been the vanguard of the progress attained in HPM source development.

Chapter 12 concludes this book by discussing alternative approaches for generating high-power microwaves that were not discussed elsewhere in the book. It also isolates and enumerates the specific scientific challenges that remain to be conquered before practical military HPM systems can flourish. In some sense, the HPM community is gradually adopting many of the engineering techniques used by the conventional tube community. The question that remains is whether continued progress in generating high-power microwaves will require the expensive, though time-proven, techniques of the conventional tube community, or whether advances in the understanding of source physics, coupled with advances in enabling technologies, will lead to compact, portable HPM sources that will find practical embodiments in the new millennium.

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