

High Power Microwave Sources and Applications

E. Schamiloglu

Department of Electrical & Computer Engineering, University of New Mexico,
Albuquerque, NM 87131 USA

Abstract — There has been considerable interest recently in high power microwave (HPM) sources for nonlethal directed energy weaponry applications. Many of these sources that are being developed are derivatives of sources that are well known to the vacuum electronics community. Others are unique to the HPM community and have no analog in traditional microwave sources. For electronic attack (referred to in the media as the “e-bomb”), HPM sources are being developed that provide peak powers that exceed 1 GW at frequencies on the order of 1 GHz in short pulses, typically on the order of 100 ns. The technology that is used to drive such sources has its roots in pulsed power, and a comprehensive understanding of their behavior requires the use of tools that have been developed in the plasma physics community. The ever-increasing reliance on the use of microprocessors that have increasing density of circuits packaged on a chip makes such systems increasingly vulnerable to HPM. This paper will provide an overview of HPM sources, their applications, and will highlight areas of intense, ongoing research activity.

Index Terms — Electron tubes, electron beams, electromagnetic transient propagation, electromagnetic radiation effects.

I. INTRODUCTION

High power microwaves (HPM) is an imprecise term used by several communities [1]. In the DoD it pertains primarily to the generation of high peak power bursts of narrowband (coherent) electromagnetic radiation spanning the frequency range of approximately 1GHz to 100 GHz. The technology used to generate such sources is often based on pulsed power [2], although more traditional modulator-based drivers are used as well, particularly at the higher frequencies where cw operation can be supported for time scales of 10's minutes. Another connotation of HPM in the DoD is the generation of ultra-wideband electromagnetic radiation [3]. Here the output frequency of the devices can range over many decades in frequency, from 10's MHz to 10's GHz. Although both the narrowband and ultra-wideband sources are referred to as HPM, the technologies involved in generating the electromagnetic radiation is very different. Narrowband sources ideally require monoenergetic electron beams in order to satisfy some synchronism condition with electromagnetic

waves. The HPM is then generated at the expense of the electron beam's kinetic energy. The driving electron beam pulses range from 10's-100's ns in duration. Ultra-wideband sources, on the other hand, use no electron beam. In fact, the ideal driver would be a δ -function generator, in other words, a high voltage spike with as short a rise time as possible. This high voltage spike is then coupled to an antenna that is optimized to radiate across the output frequency range. In this sense, narrowband HPM sources require a higher level of technical sophistication, and are analogous to lasers. Ultra-wideband sources, on the other hand, are less sophisticated and are analogous to flash bulbs.

In the DoE HPM pertains to high average power sources, such as those being developed by the Stanford Linear Accelerator Center (SLAC) for use in linear colliders. These devices have evolved over the past 6 decades from the original works of Hansen, the Heils, and the Varian brothers [4]. Many aspects of these devices are similar to the narrowband HPM sources of interest to the DoD, except that the peak powers generated are lower, but their average powers are considerably higher. Based on research trends, it appears that these two communities are converging in the sense of the sources being developed having overlapping technologies.

In the electromagnetic compability (EMC) community the terminology Intentional Electromagnetic Interference (IEMI) is favored over HPM [5]. In Ref. 5 the authors further expand the definition of IEMI, which is summarized in Table I.

TABLE I
IEMI CLASSIFICATION BASED ON BANDWIDTH

Band Type	% Bandwidth pbw $= 200 \frac{br - 1}{br + 1}$	Bandratio br
Narrow or hypoband	<1%	<1.01
Moderate or mesoband	$1 < pbw \leq 100\%$	$1.01 < br \leq 3$
Ultra-moderate or sub-hyperband	$100 < pbw < 163.4\%$	$3 < br \leq 10$
Hyperband	$163.4 < pbw < 200\%$	$br \geq 10$

In this paper we present an overview of HPM sources and applications that are of prime interest to the DoD. In this sense, we focus on narrowband HPM sources, which also corresponds to the first entry in Table I.

II. NARROWBAND SOURCES

We now present an overview of narrowband HPM sources, first in the context of how they relate to other microwave sources. Figure 1 presents a plot of peak power (from the waveform envelope) vs. average power for different categories of microwave sources. The duty factor is indicated on the diagonal lines. Conventional microwave sources range from those devices used in communications to the highest average power devices used in linear colliders. Whereas solid state devices have been gradually taking over conventional microwave sources in the lower average powers, it seems unlikely they could achieve the power levels of interest for HPM sources and linear colliders.

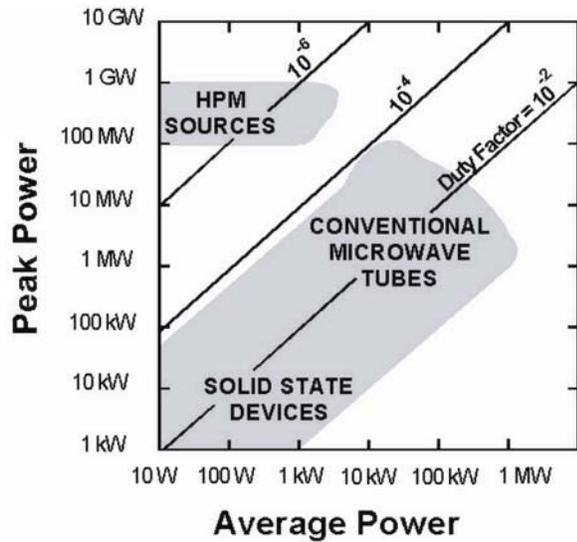


Fig. 1. Peak power vs. average power domains for microwave production [1].

Figure 2 illustrates the technical progress over several decades in the Pf^2 (power times frequency squared, also referred to as the *quality factor*) scaling of microwave sources. The relativistic devices are considered HPM. Notice that the output parameters from conventional devices have slowed considerably in recent decades, whereas the HPM sources experienced significant increase in output power during the same period of time.

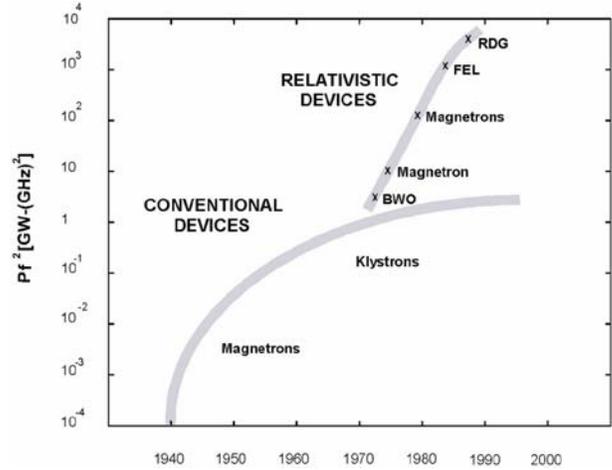


Fig. 2. Evolution of microwave devices in terms of the quality factor Pf^2 . BWO = backward wave oscillator, FEL = free electron laser, and RDG = relativistic diffraction generator [1].

Figure 3 presents a block diagram of a narrowband HPM source. Pulsed power is the technology that converts some prime power source (whether the line voltage in the laboratory, jet turbine on an aircraft, or a battery pack on an unmanned drone) into a short, properly tailored, high voltage pulse. High voltage capacitors, together with fast switching techniques, are typically used to accomplish this.

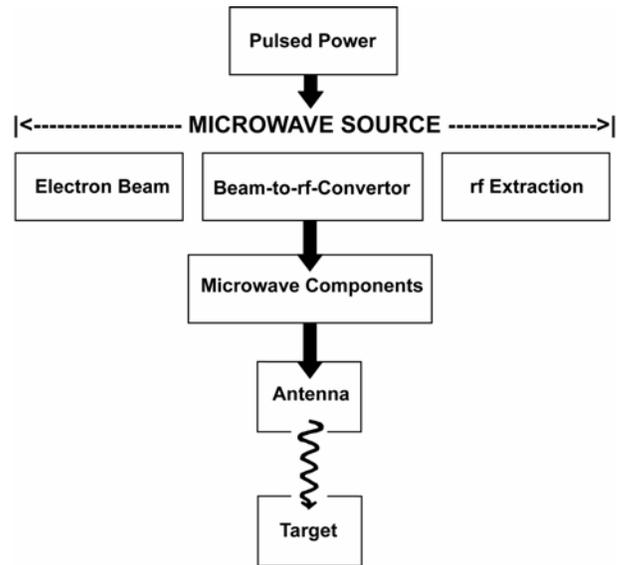


Fig. 3. Block diagram of an HPM system [1].

Once the pulsed power portion of the system has produced the desirable high voltage waveform, it is applied to an electron gun, also known as an electron beam diode. The electron beam diode produces a high-perveance¹ electron beam where space-charge effects dominate the interaction. It is because of the presence of space-charge effects that plasma physicists tend to dominate research activities in HPM.

The relativistic electron beam, once generated, propagates through an rf interaction region, which converts the beam's kinetic energy to HPM. It is the particular nature of this interaction that then distinguishes the various classes of sources. There are three basic interactions between relativistic electron beams and rf structures that produce electromagnetic radiation [6,7]: (A) Cherenkov or Smith-Purcell radiation of slow waves propagating with velocities less than the speed of light c in the medium (usually vacuum), (B) Transition radiation, and (C) bremsstrahlung radiation.

A. Cherenkov Radiation

Cherenkov radiation occurs when electrons propagate in a medium with a refractive index $n > 1$, and the electron velocity v exceeds the phase velocity of electromagnetic waves $v_{ph} = c/n$. This interaction can produce electromagnetic radiation only when the refractive index is large enough: $n > c/v$. Well-known microwave sources (and their HPM versions) based on this class of interaction include linear beam devices² such as traveling-wave tubes (TWT's) and backward-wave oscillators (BWO's).

Cross-field devices, such as magnetrons and the MILO [1], differ from the linear beam devices in that they convert the potential energy of electrons into microwaves as the electrons drift within the resonant structure. Nevertheless they can be treated as Cherenkov devices because the electron drift velocity v_{dr} in the crossed electric and magnetic fields is close to the phase velocity of a slow electromagnetic wave.

Cherenkov HPM sources have produced several GW's of output power in pulse durations ranging from 10's to a few 100 ns at frequencies ranging from 1-10

GHz. The shorter pulse duration systems have been operated at repetition rates of several 100 Hz.

B. Transition Radiation

Transition radiation occurs when electrons pass through a border between two media with different indices of refraction, or through some perturbation in the medium such as conducting grids or plates. In low frequency rf tubes these perturbations are material grids. In microwave sources such as klystrons, they are short-gap cavities within which the microwave fields reside.

Transition radiation-based HPM sources include the relativistic klystron oscillator (RKO), the relativistic klystron amplifier (RKA), and the Reltron [1]. Such devices have produced in excess of 10 GW in pulse durations of about 100 ns at frequencies near 1 GHz. The highest power devices are single-shot.

C. Bremsstrahlung Radiation

Bremsstrahlung radiation occurs when electrons oscillate in external magnetic and/or electric fields. In these devices the electrons radiate electromagnetic waves whose Doppler-shifted frequencies coincide with either the frequency of the electron oscillations Ω , or with its harmonic through $\omega - k_z v_z = s\Omega$, where $k_z v_z$ represents the Doppler-shift and s is the resonant harmonic number. Since this expression can be satisfied for any wave phase velocity, the radiated waves can either be fast (*i.e.* $v_{ph} > c$) or slow.

Coherent bremsstrahlung can occur when electron oscillations are induced in either constant or periodic fields. The best known devices in which electrons oscillate in a constant magnetic field are the cyclotron resonance masers (CRM's) (see [8] for a forthcoming comprehensive review of CRM's). The most common devices based on radiation from electrons oscillating in periodic external fields are free-electron lasers (FEL's).

Bremsstrahlung radiation-based sources are best known for their ability to produce electromagnetic radiation across a very broad frequency range that extends well above 100 GHz. They are inherently tunable and can operate continuously (cw). The gyrotron [7,8] has the distinction of generating the highest average output microwave power.

Within this class of sources there is one that stands out as a very different type of source, that is the virtual cathode oscillator or vircator [1]. In the vircator a high current electron beam propagates into a region where its space-charge depression limits the current to a lower value. This is often accomplished by a sudden increase

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

² *Linear beam* implies that the electrons move axially along a linear guide magnetic field produced by an external coil. In contrast, in *cross-field* devices the electrons move across magnetic field lines produced by an external coil.

in the radius of the metal drift tube through which the beam propagates. As the beam enters the larger radius region, the beam slows and some of the electrons reverse direction, producing a region of high space-charge density and an electrostatic potential depression known as a virtual cathode. Two distinct processes of radiation generation can occur: the virtual cathode space-charge cloud produces radiation as it oscillates at the plasma frequency, and electrons radiate as they reflex back and forth. In general, these mechanisms are competitive and do not occur at the same frequency, which is why vircators have the lowest efficiency of HPM devices. Vircators have radiated output powers in excess of 1 GW at frequencies from 1 to a few GHz.

III. APPLICATIONS

The applications for HPM sources are in areas where either high average or high peak power microwaves are required. For the case of high average power sources, applications driving their development include: 1) heating and current drive of plasmas in tokamaks and other confinement schemes (high average power oscillators at frequencies > 100 GHz), 2) rf acceleration in high energy linear colliders (high power, narrowband amplifiers, from 10 GHz to over 100 GHz), 3) radar and communication systems (moderate average power, broad-bandwidth amplifiers in the 10's GHz frequency range), and finally 4) active denial technology for non-lethal crowd control (high average power at 94 GHz).

For the case of high peak power narrowband sources, the development of sources has been driven primarily by the DoD's interest in developing non-lethal directed energy weaponry for electronic attack [11], referred to in the media as the "e-bomb." In this case, peak output powers on the order of 1 GW at frequencies on the order of 1 GHz in pulse durations as long as possible, but typically on the order of 100 ns are desirable. Repetitive pulse capability is also desirable, but becomes increasingly difficult at the highest output powers and longest pulse durations.

IV. AREAS OF ONGOING RESEARCH

The high peak power sources that are presently receiving the greatest attention include the relativistic magnetron and the RKA. Although a great deal of understanding through experimentation and particle-in-cell computer simulations has been gained regarding beam-particle interactions in such devices over the past decade, several limitations, such as pulse shortening and inadequate cathodes, have also been identified [1]. As a

result HPM sources are increasingly incorporating many of the protocols that commercial microwave tube manufacturers have used for decades. It is also expected that the commercial manufacturers will also benefit from the research performed in the HPM community, particularly from the sophisticated computational tools that have been developed to address the complexity of the HPM problem. Investment by the DoD in research into new cathodes has been made in terms of a new university research program that was announced for FY 2004 [12], which highlights the importance of this topic.

In addition, although many narrowband sources have demonstrated operation in the laboratory, the ability to transition them into mobile platforms is limited, in part, by the bulkiness of the pulsed power systems used to drive them. This latter issue was the impetus to support research into a better understanding of components in pulsed power systems that could lead to future systems being designed to be much more compact [13].

ACKNOWLEDGEMENT

The author wishes to thank Dr. R.J. Barker, AFOSR, for his suggestions and careful reading of this paper.

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