Circuit and Electromagnetic System Design Notes

Note 50

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An Overview of High-Power Electromagnetic (HPEM) Radiating and Conducting Systems

Dr. D. V. Giri
Pro-Tech, 11-C Orchard Court, Alamo, CA 94507-1541
Giri@DVGiri.com www.dvgiri.com

Dr. F. M. Tesche
Department of ECE, Clemson University, Clemson, SC 29634-0915
Fred@Tesche.com www.tesche.com

Prof. Dr. Dr. – Ing. E. h. Carl E. Baum
Department of ECE, University of New Mexico, Albuquerque, NM 87131-0001
carl.e.baum@ieee.org www.ece.unm.edu

ABSTRACT

Diverse activities of civilized societies such as civil defense, air traffic safety and control, police, ambulance, communication and internet commerce are becoming increasingly dependent on advances in computer and electronic systems. While this dependence results in enhanced quality of service, it comes at the price of increased vulnerability to a wide variety of threats to the society's infrastructure. One of the ways of ordering potential intentional electromagnetic environments (IEME) is based on frequency of coverage of the threat environment. In this paper, we will outline this classification, which is also consistent with current and emerging technologies in HPEM generation. Many examples of HPEM generators (from wall socket to radiated waves) are described here. In addition, there exists an HPEM system operating at ~ 100 GHz designed to impair the functioning of people without causing serious physiological damage for crowd control application.

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An Overview of High-Power Electromagnetic (HPEM) Radiating and Conducting Systems

1. Introduction

HPEM systems for the present purpose can be classified broadly into two groups.

1. **Anti-electronics:** designed to destroy or impair hardware, munitions or electronics with the intent to stop an enemy's systems from functioning.
2. **Anti-personnel:** designed to impair the functioning of people without causing serious physiological damage.

This classification and the various sub-classifications are shown in Figure 1.

1.1 Anti-material Technologies

It is well established that sufficiently intense electromagnetic (EM) signals in the frequency range of 200 MHz to 5 GHz can cause upset or damage in electronic systems. This induced effect in an electronic system is commonly referred to as intentional electro-magnetic interference (IEMI). Such intentional electromagnetic environments (IEME) could be radiated or conducted. One way of classifying the HPEM environments is based on the frequency content of their spectral densities as "narrowband", "moderate band", "ultra-moderate band" and "hyperband". To characterize these environments, we consider the *bandratio* of the EM spectrum $br = (f_h / f_\ell)$. Using the inherent features of *br* in a manner consistent with the emerging EM field production technologies, the definitions for bandwidth classification presented in Table 1 has been formalized [1, 2].

TABLE 1

IEME CLASSIFICATION BASED ON BANDWIDTH

Band type	**Percent bandwidth** $pbw = 200\left(\frac{br-1}{br+1}\right)$ (%)	**Bandratio** ***br***
Narrow (Hypo)	< 1%	< 1.01
Moderate (Meso)	$1\% \le pbw < 100\%$	$1.01 < br < 3$
Ultra-Moderate (Ultra Meso or Subhyper)	$100\% \le pbw < 163.64\%$	$3 < br < 10$
Hyperband	$163.64\% \le pbw < 200\%$	$br \ge 10$

Note that this terminology is consistent with IEC 61000-2-13 Standard, titled "EMC, High-power electromagnetic (HPEM) environments -- radiated and conducted". We observe that the definition of upper and lower significant frequencies as the 3 dB frequency points are not always feasible. For this reason, the lower and upper frequency points are defined by using weighted energy norms [3, 4] considering the range in which 90% of the energy is contained. Such weighted norms have the property of weighting the high- and low-frequency portions approximately equally. One can provide examples of HPEM generators that employ current and emerging technologies, for each category of the four-band classification. The above classification is useful in describing potential HPEM environments. In the case of HPEM waveforms, we stipulate the lower frequency limit to be 1 Hz if there is a large dc content in the spectrum (not applicable to radiating systems).

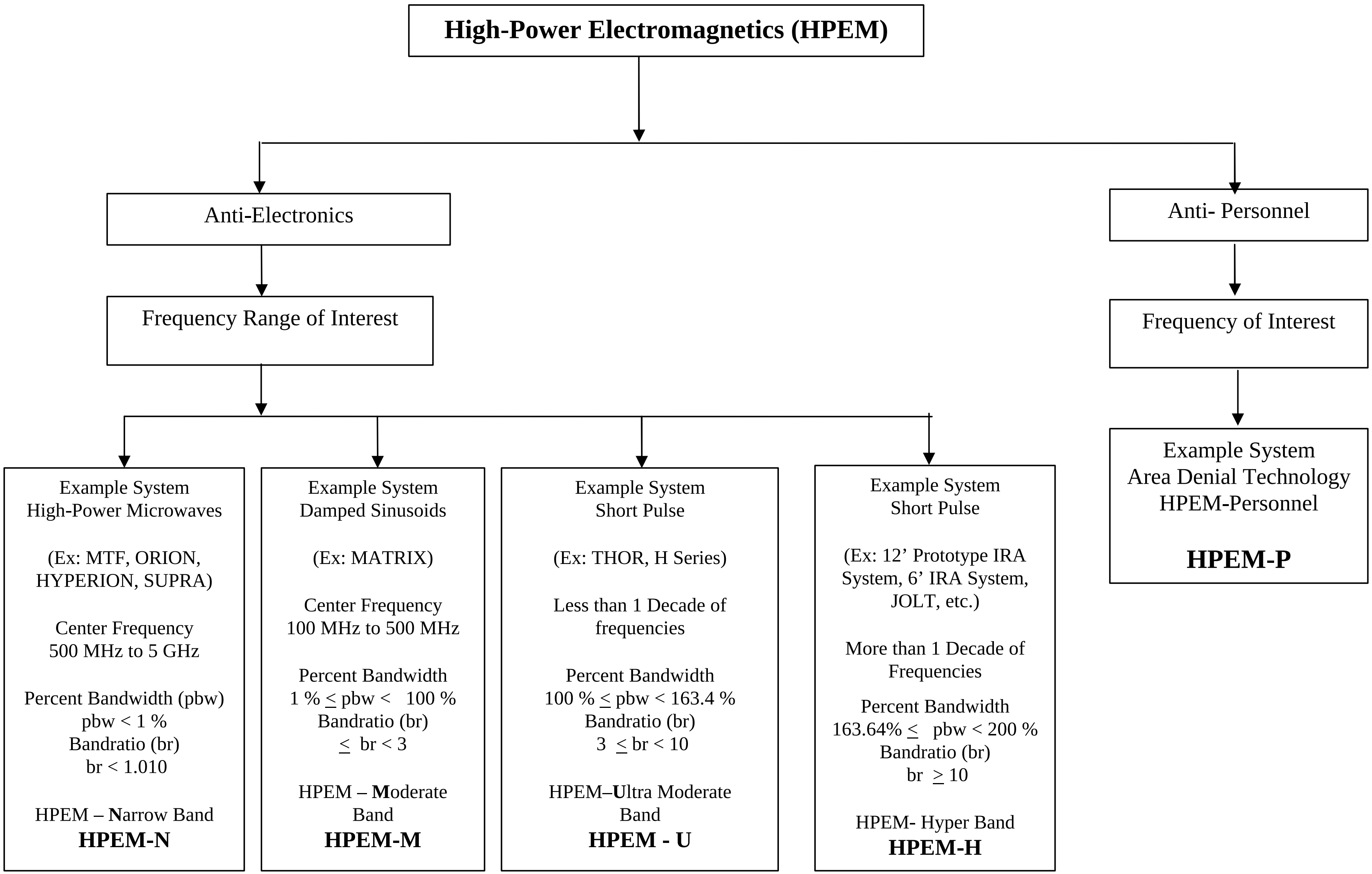


Figure . Classification of HPEM.

While considering the interaction between an electronic system and a high-power electromagnetic beam from a source at some distance away, there are various factors to be considered. Baum [5] has examined these factors going from the source to the system, as illustrated in Figure 2.

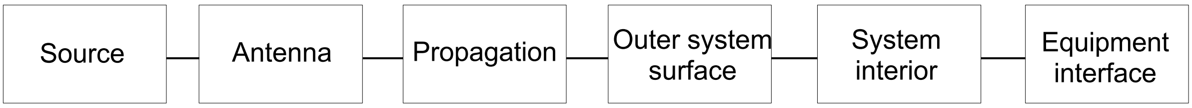


Figure 1. Factorization of transfer function from HPEM source to system.

A maximum response is normally achieved by the use of highly resonant exciting waveforms (such as damped sinusoids). The factorization shown in Figure 2 is applicable primarily to narrow and moderate band HPEM.

Conducted HPEM environments are also a potential threat to electronic equipment connected to power and communication lines [6, 7]. In most modern buildings, there is a personal computer on nearly every desk, and these computers are typically connected to the power supply and to a telephone cable or local area network (LAN), which make them vulnerable to conducted and interfering HPEM signals.

2. Narrowband Systems (*pbw* < 1 %)

High-power microwave (HPM) (≥ 100 MW) sources operating in a single-shot or with tens or hundreds of Hz repetition rates are being developed in various countries. This technology is reaching power levels in the GW range and is frequency agile. These sources can be used to create intense electromagnetic fields in the range of ~ 500 MHz to 3 GHz that can couple to targeted systems and cause electronic upset or damage. While several nations may not be interested in developing or deploying HPM weapon systems, they will be compelled to understand and protect their military assets against this potential threat. Several HPM facilities in the frequency range of 0.7 GHz to 3 GHz exist [8]. Examples are shown in Table 2. However, it is possible that some smaller-scale versions of such systems could be used for destructive purposes, if acquired by organizations or groups intent upon harming other societies. Therein lays the potential threat in the present context of civilian and military electronics systems and infrastructure.

TABLE 2 Examples of High-Power Narrowband Systems

Feature	MTF SWEDEN	ORION U.K.	Hyperion FRANCE	Supra GERMANY
RF Source	Conventional Tubes	Relativistic Magnetrons	Relativistic Magnetron & Reltrons	Reltrons
Frequency	1.3, 2.86, 5.71, 9.30 and 15 GHz	1 – 3 GHz	1.3-1.8 GHz (Magnetron) 2.4 – 3.0 GHz (Magnetron) 0.72 – 1.44 GHz(Reltron)	0.675 – 1.44 GHz
Max. Power	25, 20, 5, 1, 0.25 MW as a function of frequency	350 MW of microwave power ; 5 GW pulse power 500 kV; 50Ohm	---	400 MW – 200 MW
Max. PRF	1000,1000,1000 1000 and 2100 Hz	Single shot to 100 Hz	----- (Magnetron) 1 Hz (Reltron)	10 Hz
Max. Pulse Duration	5, 5, 5,3,8 & 0.53 μs	500 ns	100 ns Magnetron 200 ns Reltron	> 300 ns
Field Level	---	---	40 kV/m (with Reltron) 60 kV/m (with Magnetron)	70 kV/m at 15 m

Baum [9] has postulated that the narrowband systems can also be built with a half-reflector and a ground plane (Figure 3). Half a pyramidal horn can be bonded to the ground plane with its phase center coincident with the focal point of the reflector.

The pyramidal horn is fed from underneath the ground plane in an E-plane bend by the usual WR-975 rectangular waveguide for 1 GHz operation. The ground plane provides an electromagnetically shielded volume in which the narrowband source and ancillary equipment can be housed The RF source is typically a narrowband high-power microwave generator such as a Magnetron, Reltron, or Klystron. If space is a consideration, e.g., on an airborne platform, Baum [10] has suggested a high-power scanning waveguide array illustrated in Figures 4a, b and c.

This system involves subdivision of rectangular waveguide to form an array. [(N-1) sheets → N sub-guides → N sub-apertures] and avoids the use of small coupling holes/slots in a waveguide. Beam scanning is accomplished by varying the frequency.

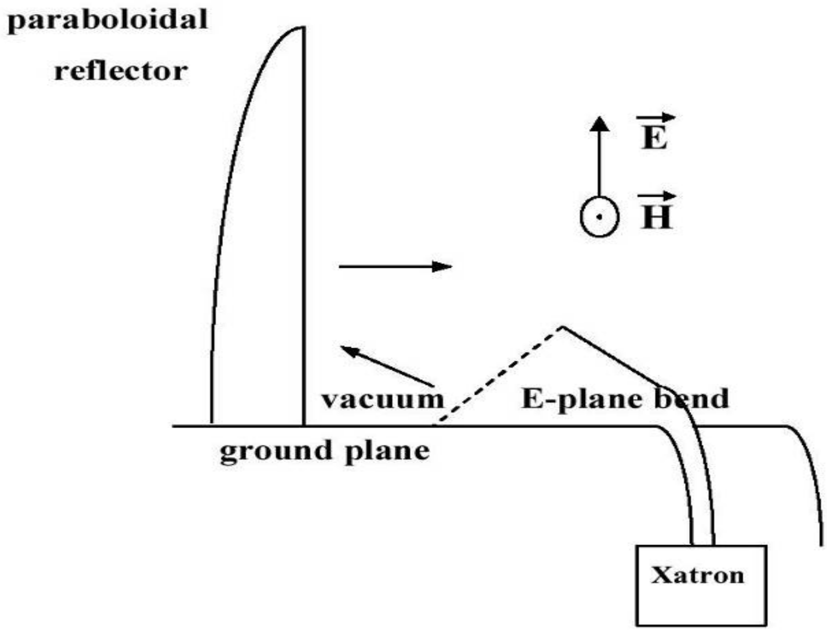
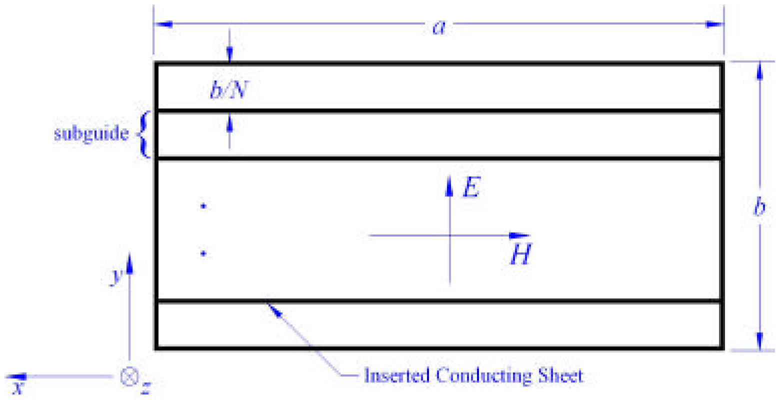
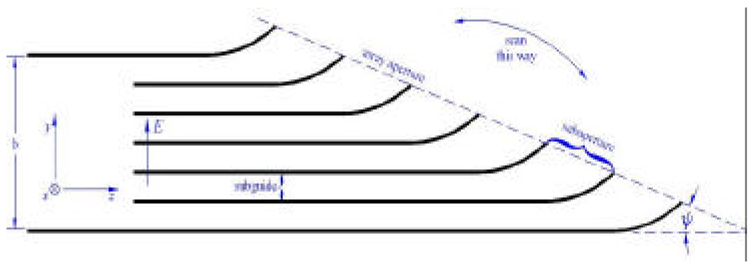


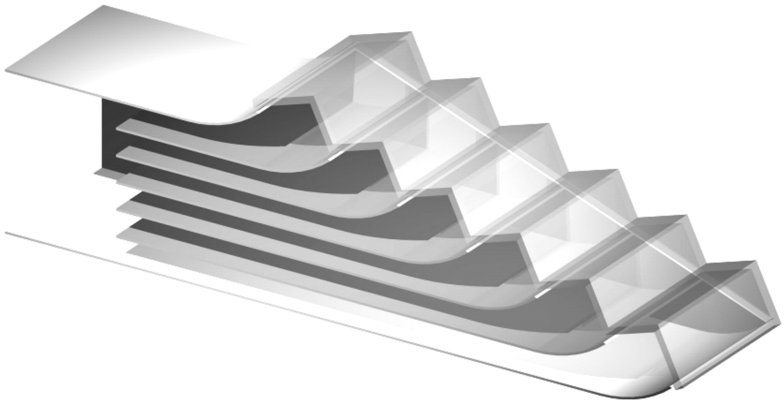
Figure 2. Half-reflector Phaser.



a. Cross section of a split-waveguide.



b. Side view of a split-waveguide.



c. Three-dimensional view of a split waveguide.

Figure 3. High-Power Split-Waveguide Antenna [10].

3. Moderate Band Systems (1 % < *pbw* < 100 %)

Moderate band systems (source and antenna) have been built in the range of 100 MHz to 700 MHz and have been called the Dispatcher. The term Dispatcher stands for Damped Intensive Sinusoidal Pulsed Antenna, Thereby Creating Highly Energetic Radiation. Baum [11, 12] has described certain systems that integrate an oscillator into the antenna system. Examples are: (a) a low–impedance quarter wave transmission line oscillator feeding a high-impedance antenna, and (b) a low-impedance half wave transmission line oscillator feeding a high-impedance antenna. The transmission line oscillator would consist of a quarter or half wave section of a transmission line (in oil medium for voltage stand off) that is charged by a high voltage source. This is schematically shown in Figure 5 where the antenna is a TEM - fed half reflector.

The switched oscillator concept shown in Figure 5 has been realized in hardware and has been termed the MATRIX [13, 14]. The oscillator is charged up to 150 KV to 300 kV and the frequency is adjustable in the range of 180 MHz to 600 MHz. This system radiates a damped sinusoidal waveform with a percent bandwidth of about 10%. An advantage in energizing a high-impedance antenna (100 Ω in the case of a half-reflector shown in Figure 5) from a low impedance source (~ 5 Ω) is that the voltage into the antenna nearly doubles, leading to higher radiated fields.

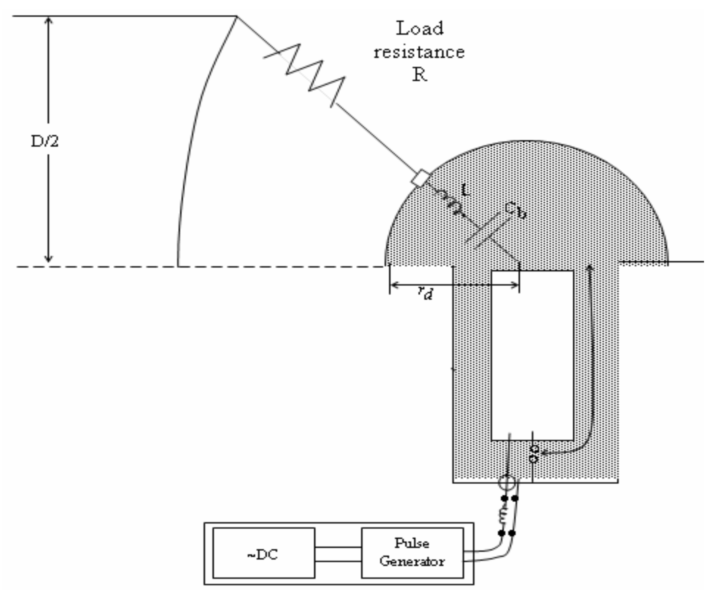


Figure 4. An oscillator that switches into an antenna.

4. Ultra-moderate Band Systems (100 % < *pbw* < 163.64 %) or (3 < *br* < 10)

Some of the H-series systems (for example H-2) built at the Air Force Research Laboratory, Kirtland AFB, NM have bandwidths that qualify them as ultra-moderate systems. Specifically, the H-2 generates a 300 kV/250 ps/~ 2 ns pulse feeding a TEM horn that radiates a pulse of 43 kV/m at a distance of 10m ($r \cdot E_{peak}$ ~ 430 kV). A second example is the THOR system [15] with a 1 MV pulse producing a peak electric field of 68 kV/m at 10m($r\ E_{peak}$ = 680 kV) with a FWHM of 400 ps. The bandwidth is from 200 MHz to 1 GHz or a br ~ 5 and a pbr ~ 133 %.

5. Hyperband Systems (163.64 % < *pbw* < 200%) or (*br* > 10)

Since they were first proposed in 1989 [16], paraboloidal reflectors fed by TEM transmission lines have received significant attention, owing to their main attractive property of extremely wide bandwidth, without the adverse effects of dispersion. They have been called the impulse radiating antenna (IRA) systems and a photograph of an example, the prototype IRA in Figure 6.

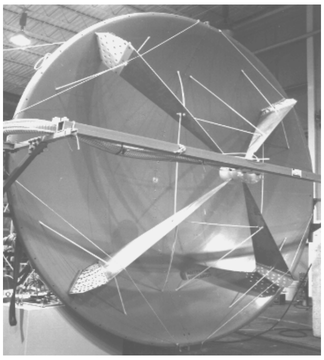


Figure 5. Photograph of the 3.67m Prototype IRA System.

The bandwidth associated with time-domain antennas is to be distinguished from the approximately 10 to 1 bandwidth of the so called frequency independent antennas such as the log-periodic antenna, which is highly dispersive since the phase center of the antenna is not fixed. Different CW frequencies applied to a log-periodic antenna are radiated from different portions of the antenna, which makes it dispersive if all of the frequencies are applied at the same time as in a pulsed application. Reflector IRAs overcome this problem and even have equivalent electric and magnetic dipole moments characterizing the low-frequency performance. Even the dipolar radiation at low frequencies is along the optical axis of the reflector. Many optimal reflector IRAs have been designed, fabricated and tested. Additional details may be found in [17, 18, and 19].

5.1 JOLT (Hyperband Radiator)

The JOLT is a half-IRA system [20, 21] with a 3.05m diameter, paraboloidal, commercial microwave reflector that has been cut in half and flanged for attachment to the ground plane. The transient energy source located at the focal point of this reflector launches a near-ideal TEM spherical wave on to the reflector through a polypropylene lens to be reflected as a collimated beam. A photograph of the JOLT system and a sample boresight measurement are shown in Figures 7 and 8.

Figure 6. Photograph of JOLT Radiator.

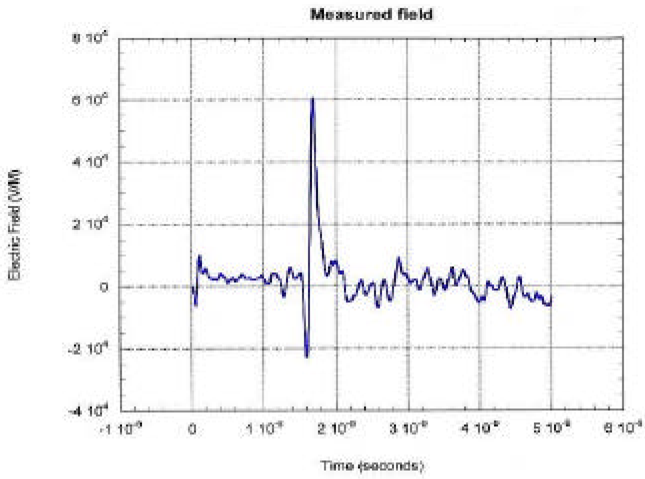


Figure 7. Measured electric field at a boresight distance of r = 85m.

The JOLT is a high-voltage transient system built at the Air Force Research Laboratory, Kirtland AFB, NM during 1997-1999. The pulsed power system centers on a very compact resonant transformer capable of generating over 1 MV at a pulse repetition frequency of 600 Hz. This is switched via an integrated transfer capacitor and an oil peaking switch onto an 85 Ω half IRA.

This unique system will deliver a far radiated field with a full-width half maximum (FWHM) on the order of 100 ps, and a field –range product ($r \cdot E_{peak}$) of ~ 5.3 MV, exceeding all previously reported results. A representative measured far-electric field is shown in Figure 8. It is seen that the impulse-like radiated field from the JOLT has an extremely large bandwidth ranging from about 40 MHz to about 4 GHz or a band ratio of 100. Such HPEM environments are useful in specialized applications. Hyperband systems can be built in many forms such as reflector IRAs described above, or TEM horns [22] and lens IRAs [23]. They have useful applications such as:

- **Disrupter** (**D**isrupting **I**ntegrated **S**ystem, **R**eleasing **U**ltra-**P**ower **T**ransient **E**lectromagnetic **R**adiation)
- Buried target detection such as de-mining
- Hostile target detection and identification
- Space debris detection
- Periscope detection
- Source for vulnerability studies via transfer functions
- High-power, hyper-wideband jammers
- Law-enforcement applications such as “seeing through walls”
- Electrical characterization of materials (e.g., wave propagation measurements in materials such as rock, concrete etc.)
- Industrial applications (detection of leaky or defective pipes)
- Detection of human beings in earthquake rubble
- Searching for avalanche victims
- Artillery application

6. Area Denial Technology

We present this example based on a fact sheet on this system, published by the Office of Public Affairs posted at Air Force Research Laboratory’s (AFRL) website at http://de.afrl.af.mil. Figure 9 shows the system hardware. This section is placed in quotation marks, since this material is extracted from AFRL’s website.

Figure 8. Photograph of the demonstration hardware.

“This is a breakthrough non-lethal technology that uses millimeter-wave electromagnetic energy to stop, deter and turn back an advancing adversary from relatively long range. It is expected to save countless lives by providing a way to stop individuals without causing injury, before a deadly confrontation develops. The technology was developed by the Air Force Research Laboratory and the Department of Defense's Joint Non-Lethal Weapons Directorate. This non-lethal technology was developed in response to Department of Defense needs for field commanders to have options short of the use of deadly force. Nonlethal technologies can be used for protection of Defense resources, peacekeeping, humanitarian missions and other situations in which the use of lethal force is undesirable.

Active Denial Technology uses a transmitter to send a narrow beam of energy towards an identified subject. The electromagnetic radiation reaches the subject and penetrates less than 0.4 mm into the skin, quickly heating up the skin's surface. Within seconds, an individual feels an intense heating sensation that stops when the transmitter is shut off or when the individual moves out of the beam. Despite the sensation, the technology does not cause injury because of the low energy levels used. It exploits a natural defense mechanism that helps to protect the human body from damage. The heat-induced sensation caused by this technology, is nearly identical to the sensation experienced by briefly touching an ordinary light bulb that has been left on for a while. Unlike a light bulb, however, active denial technology will not cause rapid burning, because of the shallow penetration of the beam and the low levels of energy used. The transmitter needs only to be on for a few seconds to cause the sensation.

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Operational System

Currently, concept demonstration is underway for a vehicle-mounted version. Future versions might also be used onboard planes and ships. The vehicle-mounted version will be designed to be packaged on a vehicle such as a High Mobility Multi-purpose Wheeled Vehicle (HMMWV, more commonly referred to as a Humvee) (see Figure 10).

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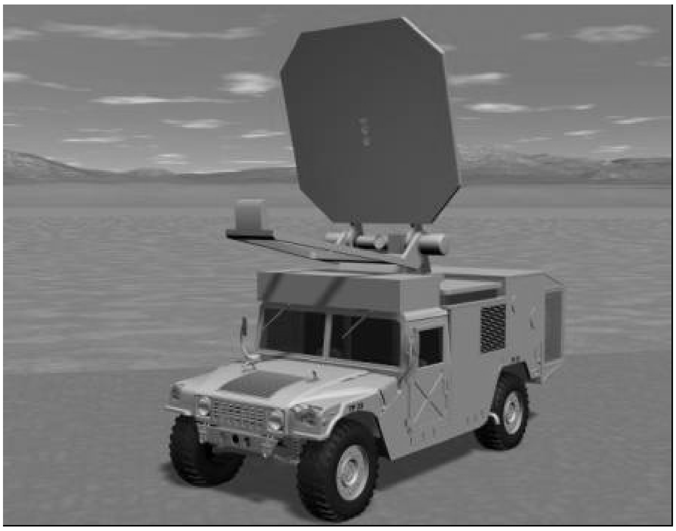

Figure 9. The Vehicle-Mounted Active Denial System Concept

7. Summary

We have presented the 4-way categorization of HPEM environments based on bandwidth. This categorization is based on emerging technologies and example systems in each of the four categories are also described. In addition, illustrative examples of hyperband radiators, which are finding many useful applications both in the military and civilian sectors, are listed. While these anti-material HPEM systems are in the frequency range of ~ 100 MHz to 5 GHz, there exists an anti-personnel system at ~ 94 GHz termed Area Denial technology, which is also briefly described here.

8. References

1. D. V. Giri, "Classification of Intentional Electromagnetic Interference (EMI) Based on Bandwidth", AMEREM 2002, Annapolis, Maryland, 2-7 June 2002.

2. D. V. Giri and F. M. Tesche, "Classification of Intentional Electromagnetic Environments (IEME)", *IEEE Transactions on Electromagnetic Compatibility*, Volume 46, Number 3, August 2004.

3. D. Nitsch, F. Sabath, H.-U. Schmidt and C. Braun, "Comparison of the HPM and UWB Susceptibility of Modern Microprocessor Boards", *System Design and Assessment Note 36*, July 2002.

4. C. E. Baum and Daniel H. Nitsch, "Band Ratio and Frequency-Domain Norms", *Interaction Note 584*, 1 May 2003.

5. C. E. Baum, "Maximization of Electromagnetic Response at a Distance", *IEEE Transactions on Electromagnetic Compatibility*, Volume 34, No. 3, Special Issue on High-Power Microwaves, Guest Edited by D. V. Giri, August 1992, pp148-153.

6. V. Fortov, F. Loborev, Yu. Parfenov, V. Sizranov, B. Yankovskii, and W. Radasky, "Estimation of Pulse Electromagnetic Disturbances Penetrating into Computers Through Building Power and Earthing Circuits", Metatech Corporation, Meta-R-176, December 2000.

7. V. Fortov, Yu. Parfenov, L. Zdoukhov, ,R. Borisov, S. Petrov, L. Siniy, and W. Radasky, "Experimental Data on Upsets or Failures of Electronic Systems to Electric Impulses Penetrating into Building Power and Earthing Nets", Metatech Corporation, Meta-R-187, December 2001.

8. F. Sabath, M. Bäckström, B. Nordstrom, D. Serafin, A. Kaiser and D. Nitsch," Overview of Four European High-Power Microwave Narrow-Band Test Facilities,"

IEEE Transactions on Electromagnetic Compatibility, Volume 46, Number 3, August 2004.

9. C. E. Baum, "Phaser Utilizing a Half Reflector and a Ground Plane", *Microwave Memo 9*, 15 July 2000.

10. C. E. Baum, "High-Power Scanning Waveguide Array", *Sensor and Simulation Note 459*, September 2001.

11. C.*E. Baum, "Switched Oscillators," Circuit and Electromagnetic System Design Note 4*5, 10 September 2000.

12. C. E. Baum, "Antennas for Switched Oscillators," *Sensor and Simulation Note 455*, 28 March 2001.

13. W. D. Prather, C. E. Baum, R. J. Torres, F. Sabath and D. Nitsch, "Survey of Worldwide High-Power Wideband Capabilities," *IEEE Transactions on Electromagnetic Compatibility*, Volume 46, Number 3, August 2004.

14. Burger, C. E. Baum, W. Prather, R. Torres, D. Giri, M.D. Abdalla, M.C. Skipper, B.C. Cockreham, J. Demarest, K. Lee and D. P. McLemore, "Modular low frequency high-power microwave generator," Proceedings of AMEREM 2002, Annapolis, MD, June 2002.

15. W. M. Henderson, D. E. Voss and A. L. Lovesee, "The etcheron valley outdoor high-power electromagnetic test facility and the transient high output radiator", in **Ultrawideband/Short Pulse Electromagnetics 6**, E. Mokole, M. Kragalott and K. Gerlach, Editors, New York, Plenum Press, 2003.

16. C. E. Baum, "Radiation of Impulse-Like Transient Fields", *Sensor and Simulation Note 321*, November 25, 1989.

17. D. V. Giri and C. E. Baum, "Temporal and Spectral Radiation on Boresight of a Reflector Type of Impulse Radiating Antenna (IRA)," in **Ultra-Wideband Short-Pulse Electromagnetics 3**, edited by Baum, Carin and Stone, Plenum Press, 1997.

18. D. V. Giri, H. Lackner, I. D. Smith, D. W. Morton, C. E. Baum, J. R. Marek, W. D. Prather and D. W. Schofield, "Design, Fabrication and Testing of a Paraboloidal Reflector Antenna and Pulser System for Impulse-Like Waveforms," (Invited Paper), *IEEE Transactions on Plasma Science,* Volume 25, Number 2, pp, 318-326, April 1997.

19. D. V. Giri, J. M. Lehr, W. D. Prather, C. E. Baum and R. J. Torres, " Intermediate and Far Fields of a Reflector Antenna Energized by a Hydrogen Spark-Gap Switched

Pulser," *IEEE Transactions on Plasma Science*, Volume 28, Number 5, pp1631-1636, October 2000.

20. C. E. Baum, W. L. Baker, W. D. Prather, W. A. Walton III, R. Hackett, J. M. Lehr, J. W. Burger, R. J. Torres, J. P. O'Loughlin, H. A. Dogliani, J. S. Tyo, J.S.H. Schoenberg, G.R. Rohwein, D. V. Giri, I. D. Smith, R. Altes, G. Harris, J. Fockler, D. F. Morton, D. P. McLemore, K. S. H. Lee, T. Smith, H. LaValley, M. D. Abdalla, M. C. Skipper , F. Gruner, B. Cockreham and E. G. Farr, "JOLT: A Highly Directive, Very Intensive, Impulse-Like Radiator", *Sensor and Simulation Note 480,* November 10, 2003.

21. C. E. Baum, W. L. Baker, W. D. Prather, J. M. Lehr, J. P. O'Loughlin, D. V. Giri, I. D. Smith, R. Altes, J. Fockler, D. McLemore, M. D. Abdalla and M. C. Skipper, "JOLT: A Highly Directive, Very Intensive, Impulse-Like Radiator", *Proceedings of the IEEE*, Special Issue on Pulsed Power: Technology & Applications, July 2004 , edited by E. Schamiloglu and R. J. Barker, Invited Paper on JOLT, pp 1096 – 1109.

22. C. E. Baum, "Low-Frequency Compensated TEM Horn", *Sensor and Simulation Note 377*, 28 Jan 1995.

23. E. G. Farr, "Boresight Field of a Lens IRA", *Sensor and Simulation Note 370*, October 1994.