

# ULTRA-WIDEBAND SOURCE RESEARCH

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## Abstract

Ultra-wideband (UWB) microwave sources and antennas are of interest for a variety of applications such as transient radar, mine detection, and unexploded ordnance (UXO) location and identification. Much of the current research is being performed at the Air Force Research Laboratory (AFRL) at Kirtland AFB, NM. The approach to high power source development has included high pressure gas switching, oil switching, and solid state switched arrays. Recent advances in triggered gas switch technology and solid-state-switched shockline technology have opened up new possibilities for the development of much higher power systems and have thus opened the door to many new applications.

Figure 1. The 4m IRA

The research into UWB transient antennas has also made significant contributions to the development and improvement of wideband continuous wave (CW) antenna designs and has brought new knowledge about the complex behavior of ferrites, dielectrics, and resistive materials in short pulse, very high voltage environments. This has in turn led to advances in the technology of transformers, transmission lines, insulators, and UWB optics. This paper reviews the progress to date along these lines and discusses new areas of research into UWB technology development.

## I. INTRODUCTION

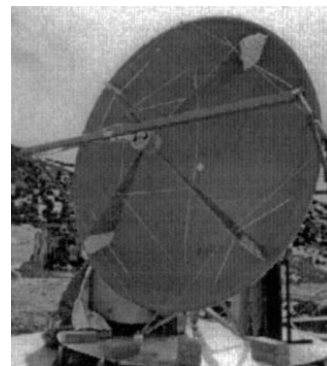
UWB research programs have been ongoing at AFRL for over ten years now, and significant progress is evident in gas and oil switched sources and in antenna technology. In a previous article, we discussed the development of UWB technology over the last decade [1]. In this paper, we will describe recent progress in sources and antennas and some exciting new developments in both gas and solid state switching and in antenna design. Interest in UWB technology is growing rapidly, and we are now seeing the technology emerging in several countries in Europe and in Russia.

## II. OIL AND GAS SWITCHING

### A. The Impulse Radiating Antenna (IRA)

The Reflector IRA, shown in Figure 1, uses high pressure hydrogen switching to produce an extremely

powerful UWB pulse from a 4m reflector [2]. With a charge of only  $\pm 60$  kV, this system generates a transient signal of 4.6 kV/m at 305m. Currently, we are in the process of modifying it to accept a 2m reflector that will use the same switch and lens assembly as the original. As a result, with a reflector only half the size of the original, the near electric field will be almost doubled to around 46 kV/m. The far field, of course, will be halved, but



for applications which are within the near field zone, this design will give a larger peak field strength, and will be much easier to handle. The voltage pulse from the 4m IRA has a risetime of around 130 ps and 1/e fall time of about 20ns. As a result, the radiated far field has a risetime of 85ps and a pulse width (FWHM) of about 130ps. The radiated spectrum of the IRA is flat within 3 dB from 35 MHz to 4 GHz.

### B. H-Series Sources

Development on the H-Series of UWB sources began in 1990 and continues today. Like the IRA, these sources use high-pressure hydrogen as their main switching medium. The latest in the series, the H-5, is a powerful, yet compact, UWB system [1]. The first prototype of the H-5 was demonstrated in March of 1997 and was later used in a Live Fire Test and Evaluation at China Lake [3]. It was operated at around 250 kV into a large TEM horn antenna and produced a peak field of 43 kV/m at 10m. The next source in the series, the H-6, is currently under development at AFRL. It is designed to generate a full 1 MV into 100 ohms with a risetime on the order of 200ps. Although the design is not complete, the performance of some of the components has been published [4-6].

With these, as with most engineering creations, improvements are continually being made. For the H-2 and H-5 sources, one of the limitations on both voltage and lifetime has been the transformer. As a result, a new concept combining the capacitive store and the transformer into one unit is being tried out on the H-2. If successful, it will also be used on the H-5 [7].

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| 14. ABSTRACT<br><b>Ultra-wideband (UWB) microwave sources and antennas are of interest for a variety of applications such<br/>as transient radar, mine detection, and unexploded ordnance (UXO) location and identification. Much of<br/>the current research is being performed at the Air Force Research Laboratory (AFRL) at Kirtland AFB,<br/>NM. The approach to high power source development has included high pressure gas switching, oil<br/>switching, and solid state switched arrays. Recent advances in triggered gas switch technology and<br/>solid-state-switched shockline technology have opened up new possibilities for the development of much<br/>higher power systems and have thus opened the door to many new applications. - The research into Figure<br/>1. The 4m IRA UWB transient antennas has also made significant contributions to the development and<br/>improvement of wideband continuous wave (CW) antenna designs and has brought new knowledge about<br/>the complex behavior of fen-&amp;es, dielectrics, and resistive materials in short pulse, very high voltage<br/>environments. This has in turn led to advances in the technology of transformers, transmission lines,<br/>insulators, and UWB optics. This paper reviews the progress to date along these lines and discusses new<br/>areas of research into UWB technology development.</b> |                                    |                                     |                                             |                                             |                                    |
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### C. Triggered Gas Switches

Precision switching is a critical technology that will allow the full exploitation of UWB radiation for a wide range of applications. Thus, AFRL is pursuing three approaches to reducing the jitter of UWB radiating systems: 1) the development of a low-jitter switching element, the Ferratron, 2) optimization of overall system design parameters and 3) introducing field enhanced triggers or laser triggers into high pressure hydrogen switches that already have high rep rate and fast risetime capability.

The Ferratron uses a ferroelectric trigger as an electron source which, when combined with high gas flow, provides reliable, low jitter triggering at high rep rates. Although the design is not yet optimized, the measured jitter of the prototype Ferratron



Figure 2. The Ferratron.

was only 63 ps using a charge voltage of 2.5 kV with a 500 ps risetime. Triggering was done in low pressure nitrogen gas [8]. For comparison, laser triggering has only produced jitter as low as 130 ps.

### D. Oil Switches and New Materials

A liquid dielectric is sometimes a desirable choice as a switching medium because it avoids the mechanical constraints imposed by high pressure gasses. Also, whereas the electrical breakdown field in gases scales with the pulse width of the charging waveform as  $t^{1/6}$ , in liquids, the breakdown field scales as  $t^{1/3}$ . Thus, a fast charging waveform, coupled with the intrinsically higher electrical breakdown fields, allows for very high inter-electrode electric fields. Of course, since the resistive phase of the transmitted pulse risetime is also larger, there is a tradeoff [9]: but risetimes on the order of 100 ps have been achieved at 200 kV and 1 kHz and at lower rep rates up to 700 kV in further tests [10] of the system described in [11]. The typical liquid used is transformer oil, but its drawback is that switch firing leaves behind particles of carbon residue which limit rep rate and will eventually short out the switch. As a result, we are investigating several other types of synthetic dielectric oil in an attempt to develop something with more desirable properties.

### E. Investigation of Corona

There is an empirical data which shows that high voltage waveforms tend to become clipped when pulsed at increasing repetition rates which may be associated with the onset of corona in the antenna. This effect can be somewhat mitigated by enveloping the antenna in an electronegative gas, it is desirable to quantify these affects for short pulse, transient waveforms. Thus, Texas Tech

University, though the AFOSR MURI program, is currently working with AFRL to understand the physics of corona onset in the subnanosecond regime [12].

### E. Low Pressure Switching

The AFRL is also investigating the physics of extremely low pressure gas in fast, high voltage switching. This is adding to our knowledge of field emission physics and the breakdown of different gasses at near-vacuum pressures and may give us some alternatives to high pressure or liquid switching mechanisms [13].

### G. Challenges and Future Directions

Future research in this area will focus on continuing to increase our knowledge of the physics of fast gas and oil switching, and introducing conventional electrical or laser triggered switches. Higher voltage and more power handling capability continue to be desirable as well as reducing the trigger time, increasing the repetition rate, and controlling the jitter. As a part of this, we will continue to investigate new switching media, especially liquids, in a joint research program with the AFRL Materials Directorate.

## III. SOLID STATE SWITCHING

### A. BASS Switches

The bulk avalanche semiconductor switch (BASS<sup>TM</sup>) is an extremely compact device that achieves sub-100 picosecond switch closure by avalanche photo-conduction through gallium arsenide (GaAs) bulk material [1]. Several switches can be illuminated by a GaAs laser diode coupled to an optical fiber splitter. They achieve 10 ps rms jitter and greater than  $3 \times 10^9$  shot lifetime, making them particularly suitable for parallel arraying to achieve greater current handling capability. The maximum switch gap is constrained by optical absorption and thermal dissipation in the GaAs, thereby capping the voltage hold off to about 17 kV. This voltage limitation has led to development of the lateral photoconductive semiconductor switch (PCSS) to increase the operating voltage and hence the radiated energy from solid-state switched arrays.

### B. Lateral PCSS Switches

The lateral-PCSS achieves 300-430 ps switch closure by avalanche photoconduction along an undoped GaAs surface gap between two specially shaped Rogowski-profile contacts. The switch remains closed, or "locked-on", beyond laser illumination, sustained until the source of charge is depleted. The Air Force Research Laboratory has tested two switch gap widths, 1.0 cm and 0.25 cm, to demonstrate the gap width effect on rise time, voltage hold off capability and lock-on voltage drop [1]. The switch topology is compatible with parallel plate transmission lines and Blumleins, which serve as energy storage for the PCSS prior to switching and a low-dispersion transmission line to an UWB antenna or

resistive load upon switching. The 1.0 cm gap demonstrated the ability to hold off up to 135 kV, but a working potential of 50 kV enables greater than  $2 \times 10^6$  shot life. However, the large gap increases the rise time (430 ps demonstrated), establishes a 5 kV voltage drop across the switch during lock-on, and only one switch can be fabricated on a 2" GaAs substrate. The 0.25cm gap has demonstrated hold off up to 32 kV, but a working potential of 20 kV is utilized for increased lifetime. The smaller gap reduces the rise time to 300 ps, reduces the voltage drop across the switch during lock-on to 1 kV, and eight switches can be fabricated on a 2" GaAs substrate, thus reducing cost.

### C. Delayed Breakdown Devices

Though laser controlled PCSS provides precise triggering required for arrayed sources, it is not ideal for all applications. PCSS are expensive because they require lasers and custom fabricated devices. Lifetime is limited by filamentation and contact degradation. For some applications alternative low-jitter triggered switches which are small, inexpensive, and have very long lifetime are needed. Sub 100-picosecond switching occurs in certain silicon PIN-diode-like structures that are rapidly overvolted beyond static reverse breakdown. There is a delay of several nanoseconds, the period of which is bias dependent, before a fast breakdown occurs to close the contact between cathode and anode. Sub-100-picosecond breakdown occurs as an ionization wave sweeps across an intrinsic material faster than the carrier drift velocity. As with the avalanche transistor and photoconductive switch, the duration of the pulse through the diode must be limited to avoid filamentation and destruction of the device [14-17]. Pulse Power Physics, Inc. successfully modeled these devices to reduce jitter in shockline structures that combine the breakdown voltage of several DBDs.

### D. Solid State Shockline

Cultivation and improvement of this technology by this team has resulted in a significant advance in high voltage triggering capability which is now being developed into solid state switched shocklines. Recently, these demonstrated the ability to multiply the charge from a 12 volt battery into a 3.2 kV transient signal with a risetime of 100 ps. The shockline device was precisely triggered at 2 kHz with only 16 ps of jitter, a remarkable accomplishment [18]. This very low jitter performance will enable such devices to be combined into high voltage arrays or single, high voltage pulsers capable of competing with today's gas and oil technology for total power while offering the additional feature of allowing the source to be electronically steered. Further development of this technology using higher energy silicon carbide (SiC) diodes is expected to enable the construction of a 350 kV module within the next year. It is expected that both of these breakthroughs will result in new products and capabilities for both the military and the private sectors.

### E. Challenges and Future Directions

Presently, solid-state switching technology is being assessed for suitability in a number of applications such as impulse radar. Depending on the device and the application, switch lifetimes up to  $10^9$  shots have been achieved. Also, PRF's of 10kHz, and power handling capability in the hundreds of megawatts have been achieved. System jitter in the prototype systems allows timing control within 10 ps. The ability to array large numbers of independently controlled elements has been demonstrated and because of this ability and the low jitter, electronic beam steering is possible and has been demonstrated. Further development of this technology is still required to address lifetime and power-handling issues; however, PCSS technology has reached a level of maturity where application is feasible.

Lifetime and power handling issues continue to be the major concerns associated with PCSS technology. The "lock-on" mechanism leaves a substantial percentage of the switching field present during the conduction phase. This can lead to large power dissipation in the devices and filamentation that shortens switch lifetime. Lifetime and power handling tend to be inversely proportionate; however a careful systems design approach can greatly enhance the lifetime and power-handling capability of a PCSS. In general, as systems and application requirements increase (i.e. PRF, power, lifetime), the difficulty in maintaining the optimum operating parameters for the PCSS increases substantially. A number of contact and material experiments are planned or underway to improve the high-voltage lateral switch design, these changes are expected to increase lifetimes to an acceptable level. Power handling issues can be addressed through series-parallel arraying.

System efficiency has become the critical issue in future application of the PCSS technology. The requirement in HPM sources is toward compact, lightweight, and high-power sources. This requires that we reduce the size of all the subsystems that make up the source while increasing the power output. At first glance, this would seem to be the impossible task; however, improvements in coupling and radiation efficiency would enhance the output power while reducing prime power requirements. The ability to make compact UWB antennas that preserve radiation efficiency and frequency spectrum is a significant challenge facing compact source design. The PCSS device cannot survive a poorly designed pulse charging system or an inefficient radiating element.

## IV. UWB ANTENNAS

### A. Impulse Radiating Antennas (IRAs)

Ultra-wideband antennas which have extremely wide bandwidth and which minimize both frequency and spatial dispersion are available in numerous sizes and shapes. The most recognizable of these is the IRA shown in Figure 1 which has been built in diameters ranging from 9" to 12' diameter and with various focal lengths depending on the application. These antennas have an

extremely wide bandwidth, usually two decades, and a beamwidth of only a few degrees.

### B. Multi-Use IRA (MIRA)

For certain applications, it is desirable to be able to vary the width of the beam or to steer the antenna without actually turning the reflector itself. This can be done with an IRA by designing it so as to be able to move the apex of the input horn with respect to the focal point of the dish. Figure 3 shows one such antenna which was built and tested at AFRL [19].

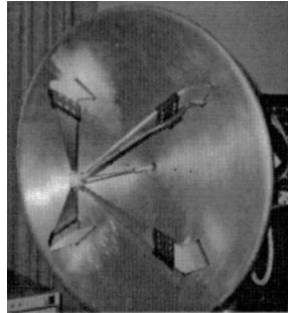


Figure 3. Multi-Use IRA.

### C. Collapsible IRA (CIRA)

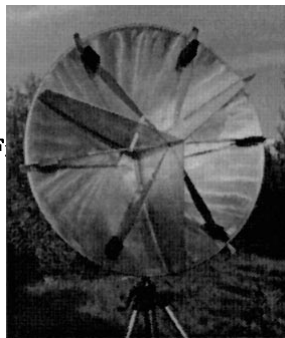
The ultra-wide bandwidth and focused beam characteristics of the IRAs have attracted the attention of many users, one of which was the U.S. Marine Corps. They needed a wideband antenna that could be used by ground troops and therefore needed to be lightweight and portable. The result was the Collapsible IRA (CIRA) shown in Figure 4 that is made of conducting fabric. This remarkable antenna folds up like an umbrella, but has surprising performance. It has been demonstrated to perform from HF to X-band.



Figure 4. The CIRA

### D. Tri-IRA

One of the primary applications is for detecting buried land mines. This requires detection of the cross-polarized field components of the scattered signal. In order to accomplish this a single antenna, a tri-antenna called the Tri-IRA was created as shown in Figure 5. It was able to successfully pick up both polarizations of the scattered field by combining the outputs from the three



in



segments of the antenna [20].

### E. Arrays

Under contract with the U. S. Air Force, Power Spectra, Inc. designed a series of UWB laboratory sources, called the GEM series, using BASS<sup>TM</sup> devices, which have demonstrated unique capabilities in low jitter, solid state switching technology. The capabilities of this system include combining power in the far radiated field by arraying many low-voltage sources, electronic beam steering, variable beam forming, and pulse repetition frequencies achieved by either simultaneous firing all array elements or by "ripple" firing the array elements in time sequence. The result is an array that can provide short bursts at a very high PRF. The culmination of this series of sources is the 144-element GEM-II array that has achieved 22.3 kV/m at 74m and a PRF of 3 kHz [1].

Recently, AFRL fabricated and demonstrated an array with a 30 x 30 cm aperture composed of a linear array of four flared TEM horns as shown in Figure 6. Each element is matched to a parallel plate Blumlein commuted with a 0.25-cm gap lateral PCSS. With a charge voltage of 17 kV, the array achieved a range-field product of 20 kV [21-22]. Further improvements in lateral-PCSS speed and voltage hold off will improve the range-field product of the array.

## V. CONCLUSIONS

There has been tremendous progress in the field of UWB electromagnetics in the last decade. In the last year, there have been two remarkable breakthroughs in fast, high voltage switching technology: low jitter, triggered gas switching and solid state shocklines. Each provides the opportunity for significant increases in our ability to radiate high voltage transient electromagnetic energy and thereby achieve substantial improvements in transient sources.

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