Ultra-Wideband Transmitter Research

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***Abstract*— The generation of ultra-wideband (UWB) pulses is a challenging problem that involves generating pulses with fast rise times on the order of 100 ps and voltages of more than 500 kV. Pulsewidths from 130 ps to a few nanoseconds (ns) are possible. A critical step involves switching high voltages with precision. The use of both gas and oil for the switching medium has been accomplished with varying results. The Air Force Research Laboratory (AFRL) is pursuing both media in the gas-switched H-series of pulsers and in studies of oil switches that promise good performance in compact packages. We are also pursuing solid-state switched systems that have demonstrated the potential for use in compact systems and in transient antenna arrays with steerable beams. This paper reviews recent progress in fast, high voltage switching and UWB transmitter development. These UWB pulsers and antennas have the potential for use in transient radar, target identification, and communications.**

***Index Terms*—Brewster angle window, gas switch, high power microwave, impulse radiating antenna, oil switch, photoconductive solid-state switch, radio frequency lens, silicon avalanche shaper, spark gap switch, transient antenna, ultra-wideband.**

I. Background

ULTRA-WIDEBAND (UWB) sources and antennas are of interest for a variety of potential applications that range from transient radar systems to communications systems. Predating the recent technology developments of the last several years were a number of important discoveries in the 1980's that led to the first UWB pulsers capable of transmitting high peak field signals through a variety of antennas. The Bournlea pulse generator is a good example of an instrument that is capable of fast rise times and a high repetition rate [1]. Using a CX1599 hydrogen thyratron as its basis, the original Bournlea pulser, made in 1986, could produce a 5-kV pulse with a rise time of 3 ns and a pulse repetition frequency (PRF) of 1 kHz. Later, when Bournlea researchers employed a ferrite line pulse sharpener for pulse compression, the rise time of the signal was reduced to 500 ps [2]. As a result, the promise of very fast, high voltage, UWB pulser was realized.

Ultra-wideband technology is of current interest to the Air Force Research Laboratory (AFRL) where research efforts have been underway for a number of years [3]–[5].[1] Sandia National Laboratories (SNL) has also produced a number of UWB sources and solid-state devices that have demonstrated substantial increases in power and repetition rates [6]–[10].

The development of new sources and antennas for the production of high power UWB fields has proceeded along several distinct lines in the past six to eight years and is now beginning to branch out into other lines of technology. This work has brought new knowledge about gas switching and insulation [11], materials breakdown [12], shock line pulser technology [13], propagation [14], and optics [15]. This research into UWB transient antennas in our laboratory and in others around the world has also contributed significantly to the development and improvement of extremely wideband continuous wave (CW) and nondispersive antenna designs [16]–[18].

The approaches have included two thrusts involving gas switched sources: very powerful, high pressure hydrogen spark gap pulsers and compact hydrogen gas switches in conjunction with high gain UWB antennas. Recent improvements in high voltage insulating oil [19], [20] and short-pulse gas switching have made significant contributions to the UWB technology. As the technology progresses, of course, it is also making possible experiments that are teaching us a great deal about material properties under high stress, short pulse conditions. The new parameter space poses significant research challenges to the attainment of more powerful UWB sources as is discussed in the next section.

The AFRL is also pursuing arrays of solid-state switched UWB pulsers and antennas that have great promise. Solid state arrays presently hold the record for peak radiated field strength in the far field of the antenna. These are discussed in some detail in a later section.

In the following sections, we report upon the research issues and progress being made on gas, oil, and solid state switching, UWB sources, and antennas.

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II. Gas-Switched UWB Sources

A. Gas Switches

The switching element is a major component of any power conditioning system and ultra-fast closing capability, along with fast voltage recovery for UWB high power microwave (HPM) generation, are desired. A fast-rising pulse is critical because the high frequency components of the transmitted spectrum are determined by the rise time. To sharpen the rise time on a pulse, a peaking switch may be used. Such switches have been part of UWB systems since the early 1970's, when they were included in electromagnetic pulse (EMP) simulators. The crux of the peaking gap is the establishment of very high electric fields between very closely spaced electrodes. The inter-electrode spacing is chosen to be as small as possible to minimize the intrinsic inductance of the spark channel, since the channel inductance will obviously limit the rise time. Spark channel inductance of less than 1 nH has been achieved with gap lengths of 1 mm and less. Because of the short gap lengths, even charge voltages of less than 100 kV can produce interelectrode electric fields in the MV/cm range with voltage doubling at the spark gap. Short gaps and high electric fields also minimize the resistive phase, which can also limit rise time. According to J. C. Martin's widely used result [21] it decreases as $E^{-4/3}$, where E is the electric field. The accuracy of this result for the extreme of UWB switching conditions is, however, uncertain. These small interelectrode distances do yield high capacitance, even for relatively small diameter electrodes. Moreover, this high spark gap capacitance, and the fast charging times lead to a strong displacement current which manifests itself as an undesirable prepulse.

To produce ultra-fast switching, the spark gap is dramatically overvolted; that is, the spark gap is charged far in excess of its self-breakdown voltage. Modern peaking gaps typically operate at gas pressures in the range of 100 atm (1400 psi) and electric fields in the MV/cm range. The self-breakdown curve for gases is known to saturate in the vicinity of 100 MV/m for pressures to 50 atm [22]. To achieve overvolting without switching at the self-breakdown voltage, the spark gap is pulse charged very quickly. This allows a large overvoltage to be achieved, and overvoltages of over 300% are achievable.

B. Oil Versus Gas Switches

High-pressure hydrogen is the gas of choice for high repetition rate, sealed, peaking switches. Hydrogen has the advantage in fast recovery time over other atomic gases. Pressures on the order of 100 atm, however, are necessary to get the required breakdown voltage. The very high pressures impose severe constraints on the geometry of the source, which in turn may introduce impedance mismatches into the transmission of electrical energy within the source.

The use of transformer oil in the peaking switch instead of high pressure gas alleviates many of the mechanical design problems. Switches using transformer oil are able to achieve higher interelectrode electric fields than those using gaseous dielectrics. The time dependency of threshold electric fields is much greater in liquids than in gases. Thus, liquid switches can be pulse charged to much higher fields than can generally be achieved in gases. The equations which estimate the rise time are strongly dependent on the electric field. Thus, the higher electric field strengths achievable in liquids can result in the shorter switch rise times.

The use of various types of hydrocarbon oil as a switching medium for the generation of sub-nanosecond rise time pulses at high repetition rates was first seriously proposed, then demonstrated, by the late P. Champney and his team at Titan-Pulse Sciences [23]. When oil fails electrically, it leaves long-lived, electrically charged streamer byproducts which decrease the effective breakdown strength of the oil. This inhibits the recovery rate of the oil, and discourages its use for repetitively pulsed systems. The Titan-Pulse Sciences team undertook a systematic investigation of flowing oil switching systems for the generation of sub-nanosecond rise time, high repetition rate pulses. This work of Titan-Pulse Sciences is widely referenced and is the basis for all wideband switches utilizing oil switches developed to date. Their effort resulted in a modulator that contained three oil switches: a transfer switch, a sharpening switch and a peaking/sharpening switch. The modulator produced pulses with a 10–90% rise time of 100 ps and performed at 200 kV, 1500 Hz and 450 kV, and 500 Hz [24]. Voltages of 800 kV were achieved with single shot conditions.

The Titan-Pulse Sciences work investigated the recovery of switches with the direction and rate of oil flow as parameters. If the flow displaces a sufficient amount of oil in the gap region, the switch breakdown strength, even in repetitive mode, is as for a single pulse. Thus, the oil flow requirements are a strong function of the switch gap, d, and a useful relationship between the switch gap spacing and the flow requirements has been determined [23]. The stressed oil region must be displaced between pulses. The volume to be displaced, then, is proportional to d^3. The displacement distance, and hence the velocity, is proportional to d. Thus, the volumetric rate goes as d^4 and the power to drive the flow goes as d^5. Thus, the flow rate requirements for peaking gaps are generally realizable, while flow requirements for switches located earlier in the pulse compression sequence may be prohibitively large. Two examples of flowing oil UWB transmitters are the SNL SNIPER and the AFRL Phoenix listed in Table I.

C. H-Series of UWB Sources

The H-Series devices use high-pressure hydrogen switches to produce powerful and very compact UWB sources. The first H-series device, the H-1, was completed in 1991, and the development has continued to the recent development of the H-5. The H-1 produced a peak voltage of 150 kV into a 2-in diameter, 50-Ω coaxial line. Although the power output was a modest 450 MW, it successfully demonstrated the concept of a high pressure (1400 psi), hydrogen-switched source. The H-2, completed in late 1992, represented a substantial improvement over the earlier version. It generated a 300-kV pulse in a 4-in diameter, 40-Ω line with a rise time of about 250 ps and a total pulse length of 1.5 to 2 ns. This provided an ultra-wide spectrum with its center frequency around 150 MHz. A

TABLE I
FIGURE-OF-MERIT FOR UWB SOURCES DEVELOPED OVER THE LAST SEVERAL YEARS SHOWING SUBSTANTIAL GAIN IN PROPAGATING ELECTRIC FIELD STRENGTH AT RANGE. THE FIGURE-OF-MERIT IS THE PRODUCT OF THE FIELD STRENGTH MEASURED IN THE FAR FIELD AND THE RANGE AT WHICH IT WAS MEASURED. IT IS AN ANTENNA-DEPENDENT QUANTITY

Source /Antenna	Year	Type	Operating Voltage (kV)	Figure-of-Merit (kV)	Comment
Bournlea / TEM horn	1986	Thyratron switch w/shockline	10	3.5	Antenna was large, 6 ft aperture TEM horn (Ref. 1)
BASS™103 / finline	1989	Photo-conductive Solid-state	12	10	Predecessor of GEM series
SNIPER / TEM horn	1991	Flowing Oil switch	250	120	SNL Source (Ref. 9)
Kentech Pulser / "kipper" shaped horn	1992	Solid state	4	4.2	Stacked parallel/series combination of 400 V switches
PHOENIX / TEM horn	1992	Flowing oil spark gap	600	200	
EMBL / TEM horn	1992	Bipolar Blumlein	750	380	SNL Source (Ref. 9)
GEM-1 / finline array	1993	Photo-conductive Solid-state	12	75	16 switches charged to 12 kV
LCO / 12' dish (UHF)	1993	H spark-gap switch	125	400	Fat dipole cylindrical sub-reflector. SNL Source (Ref. 7).
H-2+ / TEM horn	1993	H spark-gap switch	500	350	
H-3 / 18" TEM horn	1994	H spark-gap switch	400	360	Capable of 1 MV operation. Operated at reduced voltage in anechoic chamber.
GEM-2 / finline array	1994	Photo-conductive Solid-state	17	1650	144 switches charged to 17 kV
GEM-1+ / finline array	1995	Photo-conductive Solid-state	12	100	Upgraded switches. 8 switches charged to 12 kV
TLO / fat dipole	1995	See comment	1500	240	Bi-polar transmission line oscillator. SNL Source (Ref. 52)
IRA / 4m-dish	1995	H spark-gap switch	120	1300	Unique antenna/load design to maximize field at range
LCO / fat dipole (VHF)	1996	SF_6/N gas spark-gap switch	400	190	SNL Source (Ref. 52)
H-5 / TEM horn w/Brewster angle window	1997	H spark-gap switch	125	270	Designed to be compact.
H-5 / TEM horn	1997	H spark-gap switch	145	430	Simple horn antenna, allowed higher charge voltage

schematic diagram of H-2 is shown in Fig. 1 and a picture of the H-2 mated to a large TEM horn is shown in Fig. 2.

The next two pulsers in the series, H-3 and H-4, were designed to produce a much higher frequency spectrum with the center frequency between 1 and 2 GHz. The H-3 device, which is shown in Fig. 3, generates nearly 1 MV into a 40-Ω coaxial line. The radiated field from H-3 has a rise time of 130 ps and a total pulse duration of only 300 ps, as shown in Fig. 4. In order to achieve the very fast rise time, the H-3 makes use of a patented charging technique [25], [26], and a multichannel output switch. The unique transmission line-to-transmission line charging technique compresses the pulse and increases the voltage. The dual transmission line allows the first transmission line to be charged relatively slowly. When fully charged, it is switched into the second line using a high-pressure hydrogen spark gap. The fast charging of the second transmission line creates a large overvoltage on the high-pressure hydrogen, multichannel, ring gap switch. The full potential of H-3 has not been realized to date as it has only been used with small antennas. The radiated field data shown in Fig. 4 was generated using an 18-in TEM horn with a peak voltage of 130 kV. The field at 6 m was 60 kV/m.

The H-4, which is essentially a larger version of the H-3, is still in design. The goal for the H-4 is to produce 2 MV into a 40-Ω coaxial line. The waveform will have a rise time of 130 ps and a pulsewidth (FWHM) greater than 250 ps. The H-4 design is near completion, but we postponed work on the H-4 to devote our energies to the completion of a new source, the

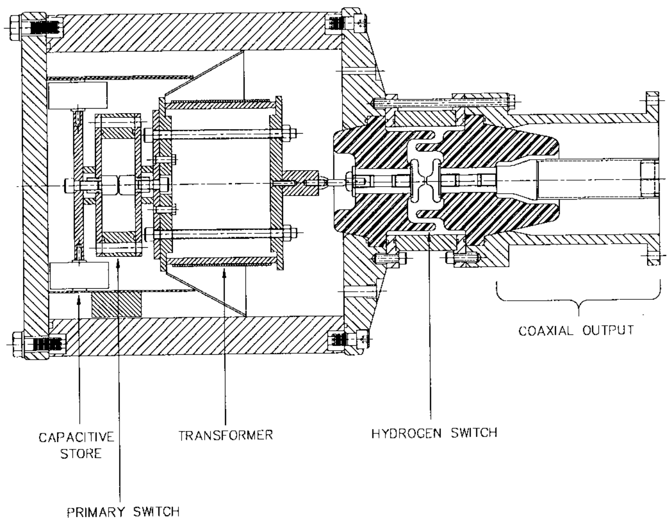

Fig. 1. Schematic of the H-2 pulser.

Fig. 2. H-2 with large TEM horn.

H-5 which is basically a higher power version of the H-2. The H-5 source was developed to be a robust, high power, ultra-wide band source that is mobile and self-contained. The design goal is to generate 500-kV pulses with a rise time of <250 ps, and a pulsewidth of 2.5 ns. The system is still in development, and thus far has reached about 250 kV. It is our goal to achieve full design voltage by the end of this year. The output voltage waveform of the pulser and radiated field waveform is shown in Fig. 5. In this case, the antenna was the 20-in unbalanced TEM horn with the Brewster angle feed, shown in Fig. 6, with the addition of a 20-in diameter polyethylene focusing lens at the aperture. The first prototype of this machine was demonstrated in March 1997. At 30-kV charge, the peak field strength radiated was 60 kV/m at a range of 4.5 m, resulting in a field-range product for this source/antenna combination of 270 kV. The H-5 was also used with the large TEM horn, and the radiated field in this configuration is shown in Fig. 7. The peak field strength measured was 43 kV/m at a range of 10 m. The rise time was 238 ps.

D. The IRA

The Reflector Impulse Radiating Antenna (IRA) shown in Fig. 8 also uses high-pressure hydrogen switching to produce an extremely powerful UWB pulse [16]–[18]. With a charge of only ±60 kV, the system generates a transient signal that was measured to be 4.25 kV/m at 305 m, which gives a field-range product of about 1.3 MV (see Table I). In the next version, we plan to increase the charge voltage to ± 180 kV, which will increase the radiated field proportionately. A smaller reflector IRA using the same lens and feed geomety can be designed as long as it has the same focal length-to-diameter (F/D) ratio. The voltage pulse from the 4-m IRA has a rise time of less than 100 ps and $1/e$ fall time of about 20 ns. As a result, the radiated field has a rise time of 85 ps and a pulsewidth (FWHM) of 130 ps plus a long undershoot which contains most of the low frequency energy. The 3-dB bandwidth of the IRA's radiated spectrum covers 35 MHz to 3 GHz. The high frequency roll-off is governed by the voltage and rise time of the gas switch and the optical correction afforded by a very precise oil and polyethylene lens at the apex. The lower frequency point is a primarily a function of the diameter of the antenna aperture and, in this case, the $\mathbf{p} \times \mathbf{m}$ compensation network at the base of each arm that allows wavelengths larger than the diameter of the antenna to be radiated [16], [27].

At late times, or low frequencies, the antenna is dominated by electric and/or magnetic dipole moments, which we represent as $\mathbf{p}$ and $\mathbf{m}$. The electric dipole is produced by the late-time charge separation or voltage appearing at the ends of the feed horns. The magnetic dipole is due to the current flowing around the loop formed by the feed horns and the dish itself. In order to minimize oscillations, the feed arms are terminated at the parabolic reflector in their characteristic impedance. The resulting balance of $\mathbf{p}$ and $\mathbf{m}$ serves to direct the low frequency radiation vector $(\mathbf{p} \times \mathbf{m})$ in the direction of the reflector's main beam. Thus, at low frequencies where the wavelength is of the order of the reflector diameter, the antenna will not radiate omni-directionally, but rather in a cardioid pattern with the maximum on the boresight of the reflector. The net effect of this is to increase the amplitude of the low frequency spectrum by about 6 dB and increases the low frequency bandwidth by a factor of two. In the case of the 4-m IRA, the low frequency limit is lowered from 70 to about 35 MHz.

These design features gave the IRA a 3 dB beamwidth of $\pm 1.2^\circ$ as determined from the measured peak electric field. The performance of this antenna and pulser system compares favorably with that of our most powerful UWB radiating system, the GEM II array, despite the comparatively modest pulser used to drive it. Even with this kind of performance, there is substantial growth potential in the combination of the gas-switched pulsers of the H-series with variants of the IRA.

E. Challenges for Gas-Switched Source Research

1) Multichannel Switching: The most powerful UWB pulsers involving gas switching have been the H-series sources that have been developed in a sequence that now includes the H-5. The designs for the H-series pulsers, H-3 and H-4 used

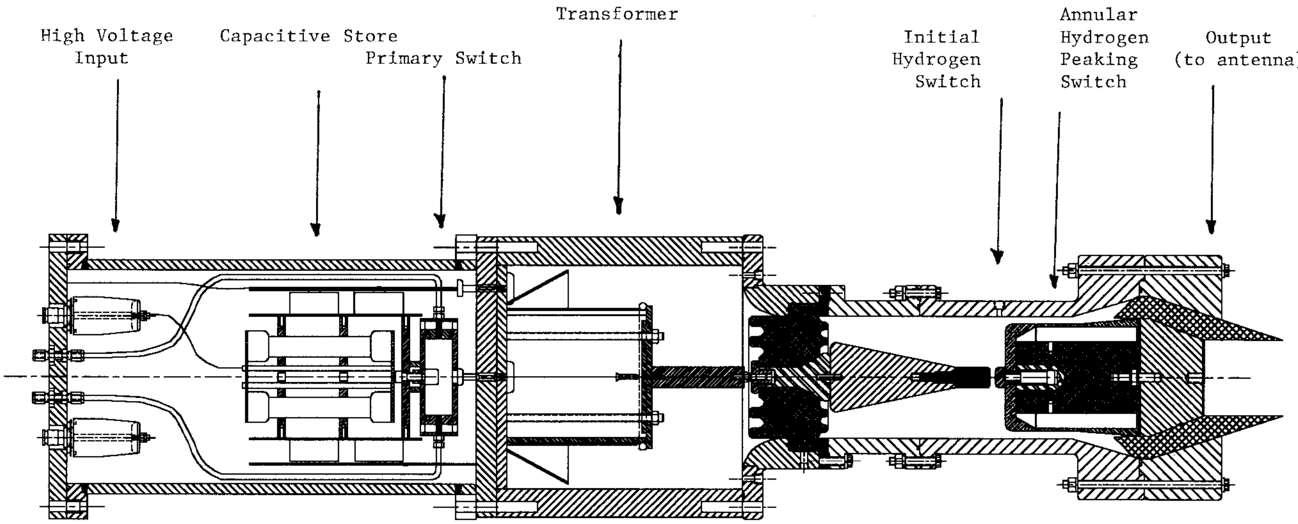

Fig. 3. Schematic of the H-3 pulser.

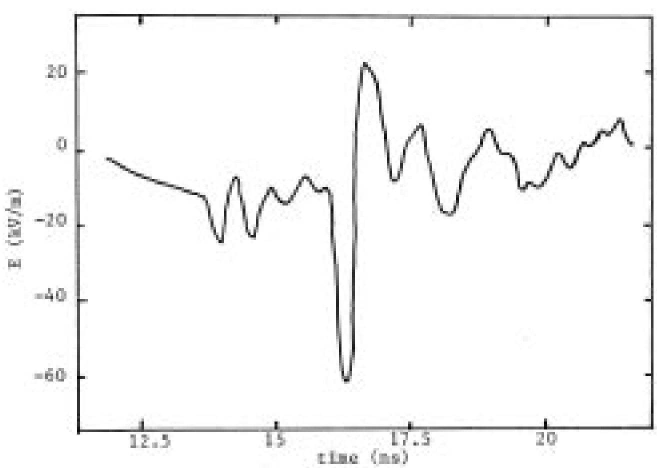

Fig. 4. Radiated field from the H-3 pulser.

a low inductance, annular multichannel switch for the final stage of the pulser. In theory, this should work because the uniform multichannel switching should provide very fast rise time. However, we found it to be difficult in practice. The dimensions of the gap and the tolerances required were found to be critical and hard to maintain in the large switch geometry at the high pressures required. As a result, our experience to date with multichannel switches has been mixed. The switch tends to break down at only one point along the circumference resulting in nonuniform launching of the electromagnetic wave (equivalently, launching a non-TEM mode). Also, a higher inductance than expected was noted. These factors made the performance erratic and increased the rise time at the output section. At this time, the H-3 is being redesigned to attempt to improve the switch performance. There is interest in investigating other means to insure multichannel switching for these pulsers. Some techniques involving the use of UV sources have been widely used to enhance the performance of gas spark gaps; however, they do not work at pressures above ten atmospheres [28].

2) Repetition Rates: Repetition rates of 2 kHz have been achieved with the H-2 and H-3 devices. This is apparently limited by the recombination rate of the gas. However, we note with interest that personnel at the Naval Surface Warfare Center, Dahlgren, VA, have suggested that pulse rates of up to 10 kHz are possible by flowing the high-pressure hydrogen gas [29]. Higher repetition rates for UWB gas switched pulsers obviously can be done, but engineering it into a compact source presents a challenge. The range of repetition rates from 2 kHz to 10 kHz is a research interest for the near term for reliable switching in configurations that preserve the low inductance required to achieve the rise times of 100 ps to 1 ns. We plan also to study a number of gases to develop data for repetitively pulsed switch use. We anticipate that further progress in UWB switching at high repetition rates is possible.

3) Insulators: For our radiating systems, insulators have been used in two ways: as a dielectric standoff and as lenses. Both uses require low loss and dispersionless materials.

Typically, the material of choice for dielectric standoffs in the H-series of pulsers has been Lexan™, a brand of polycarbonate resin manufactured by General Electric. Lexan™ has good dielectric strength and is easy to machine. While Lexan™ is strong enough that it will not flow when placed under high pressure, it does tend to creep. Moreover, Lexan™ tends to craze when it comes into contact with transformer oil, which results in a reduction of mechanical strength. Electrically, Lexan™ has the relatively high loss tangent of 0.006 at 10 GHz. The loss tangent in a transmission line structure is modeled as a conductance, which is dispersive. For a device such as H-3, with a fast rising output pulse, the propagation through the Lexan™ standoff degrades the rise time. For these reasons, alternate materials are being sought. Among the interesting candidates are Rexolite and Torlon. Rexolite 1422 is a plastic with a dielectric constant of 2.55 at 100 MHz and 2.54 at 10 GHz and a loss tangent of 0.000 47 [30]. Rexolite also exhibits considerable mechanical strength, with a tensile strength of 7000 psi [31]. Torlon, with a dielectric constant of 3.9 at 1 MHz, is another strong material which was successfully used for the high-pressure hydrogen gas enclosure on the prototype 4-m IRA [16].

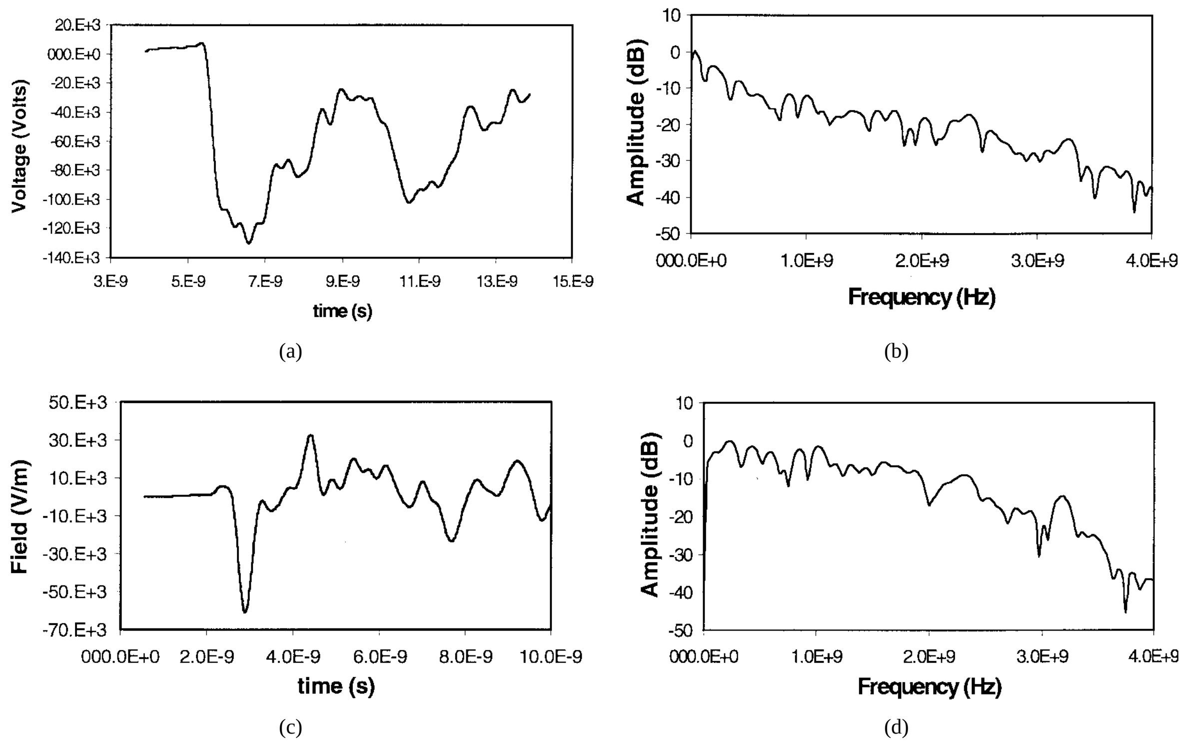

Fig. 5. Radiated field from the H-5 at 4.5 m with a Brewster angle horn and 20-in polyethylene focusing lens.

A new mixture of materials, G-10 and Kel-f is being studied for use as a switch component. This combination has a safety factor of four when pressurized to 4000 psi, and a yield strength of 16 000 psi. Kel-f is a very dense material that is impervious to gases like hydrogen.

For lenses, there is, generally, not a requirement for mechanical strength. For transient optical applications, the materials of choice have been polypropylene and polyethylene. Both of these materials are relatively dispersionless with a low loss tangent. For high power applications, the lens is generally paired with a feed through which is insulated from high voltage with transformer oil. Both polypropylene and polyethylene have a relative dielectric constant which is close to that of transformer oil, making the oil/lens interface electrically invisible. Typically, high power lenses are large, and therefore constructed from polyethylene that can be obtained in large castings. Currently, the AFRL is proposing the use of artificial dielectrics for applications such as lensing [32]. Artificial dielectrics are synthetic media which may be composed of conductive elements embedded in a natural dielectric binder. The effective dielectric constant of artificial dielectrics can be designed to be much greater than natural dielectrics. It is expected that the implementation of artificial dielectrics would result in considerable weight savings.

III. Solid-State UWB Sources

A. Stacked, Semiconductor-Based Pulsers

A proven technology for UWB applications is based on ultra-fast, semiconductor-based stacked avalanche switches. An example of a pulser employing stacked avalanche transistors is the Kentech HMP. This device demonstrates a rise time less than 100 ps, has selectable pulsewidths of up to 5 ns, an rms jitter of 10 ps, and a pulse amplitude of 6 kV per module into a 50-Ω load. The modules may be stacked in series and parallel to provide higher voltages without loss of timing performance. Kentech has demonstrated a stack that produces 24 kV into a 50-Ω load and they believe that 50 kV is achievable [33]. In the early 1990's, a module was used to conduct experiments to determine the effectiveness of UWB radar for target identification [34].

A significant advantage of stacked avalanche devices is that a laser is not required to trigger the avalanche process. These devices employ well-characterized, low-cost silicon which has four times the thermal conductivity of gallium arsenide used in the avalanche photoconductive switches. An alternative, two-terminal avalanche technology uses a drift step recovery diode (DSRD) driving a silicon avalanche shaper (SAS) in a TRAPATT mode. I. Grekhov and his colleagues at Ioffe Physical-Technical Institute, St. Petersburg, Russia, have pioneered this technology [35], [36] since the late 1970's. Recently, the AFRL, in conjunction with the University of New Mexico and Old Dominion University, has studied the physical processes of the silicon avalanche sharpeners and its operating characteristics [37]–[39]. This study confirmed the robustness of the technology and validated all the operating parameters. The DSRD opening switch achieved a rise time of 740 ps and 1.9 kV pulse amplitude, providing the 10^{12} V/s transient required to rapidly drive the SAS into reverse bias breakdown. The SAS sharpens the transient to a 100-ps rise time at the DSRD pulse amplitude level into a 50-Ω load. Life times greater than 10^{11} shots have been achieved for this system. The DSRD's have been stacked in such a way as to produce high voltage pulsers with fast transients using a SAS

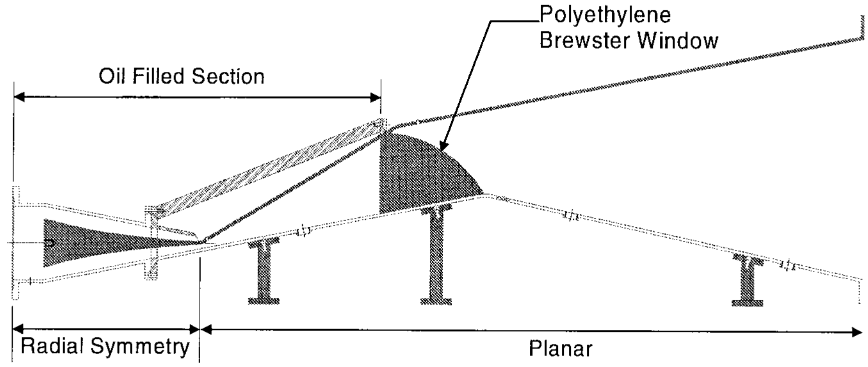

Fig. 6. Diagram of a TEM Horn with a Brewster angle window.

shaping head. One such system which was tested was an Ioffe Institute PPG-10-5 pulse generator which achieved an output amplitude of 10 kV, a rise time of less than 100 ps (with shaping head), a pulsewidth of 2 ns, and a pulse repetition rate of 5 kHz into a 50 Ω load. The developers believe that a 100-kV pulser with the same temporal characteristics is achievable.

B. Photoconductive Solid-State Switched Arrays

Photoconductive switching technology offers the potential for very low turn-on jitter, fast rise times, extremely compact packaging, and ease of phasing numerous modules. The AFRL involvement in development of photoconductive solid-state switching (PCSS) technology began in the late 1980's shortly after investigators at SNL made a new discovery while studying fast recovery switches. They showed that a "lock-on" phenomenon existed in optically activated GaAs switches at fields above 8 kV/cm [40]. This nonlinear effect caused the switch to remain conducting even after the optical pulse had turned off, and the switch rise time was not limited by the laser rise time. In addition, the optical energy required to trigger the "lock-on" mode was less than 0.1% of the energy required to trigger linear switching. This new effect opened the door for many exciting new applications that require high current switching in the fast, sub-nanosecond time regime including the generation of high-power UWB microwave sources and other applications.

The first effort with PCSS switch development was in collaboration with SNL to assess the feasibility of using photoconductive switching to improve the performance of EMP simulators. Two candidate semiconductor materials were investigated for this purpose. The first set of experiments clearly eliminated silicon as a candidate material because of the energy and rise time requirements of the laser imposed by linear switching. GaAs became the material of choice because it requires less laser energy, and the switch rise times were independent of the laser pulse rise times because of the lock-on phenomena making these devices an ideal candidate for the EMP simulator application.

A second effort involved a joint government and industry program to develop solid-state-switched HPM sources using GaAs. This effort's scope has two parallel developments that can be characterized by the switch conduction path dictated by the switch contact layout on the GaAs substrate. For switch contacts formed on opposite sides of the substrate such that the gap is *across* the substrate thickness, the conduction mechanism is through the bulk of the GaAs. This is termed bulk switching. Notable examples are the bistable optically-controlled semiconductor switch (BOSS) [41] and the Bulk Avalanche Semiconductor Switch (BASS™) [42] produced by Power Spectra, Inc. The other switch design is called a lateral switch. In this case, the switch contacts are formed on the substrate such that the gap and the main conduction path are *parallel* to the substrate surface. The development of lateral switches has been conducted through a cooperative internal DoD effort involving several service laboratories and universities.

The BASS™ device is extremely compact, and several of them can be switched with sub-100 ps rise time performance using a GaAs laser diode coupled to an optical fiber splitter. Additionally, these devices achieve 10 ps rms jitter and greater than 3×10^9 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. Under contract with the U.S. Air Force, Power Spectra, Inc. designed a series of UWB laboratory sources using BASS™ devices called the GEM series, which have demonstrated the unique capabilities of low-jitter solid-state switching technology. These capabilities include power combining in the radiated field by arraying many low-voltage sources, electronic beam steering, and variable beam forming and pulse repetition frequencies achieved by either simultaneous firing of all array elements or "ripple" firing of 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 achieved 22.3 kV/m at 74 m range and a PRF of 3 kHz [4]. The 1650-kV field-range product of the GEM-II array is the highest ever demonstrated by a UWB source, performed with a charge voltage of only 17 kV (see Table I).

The lateral-PCSS technology is being pursued in order to increase considerably the operating voltage and hence the radiated energy of solid-state switched arrays. Refractory-metal contacts shaped in a Rogowski profile, used to produce

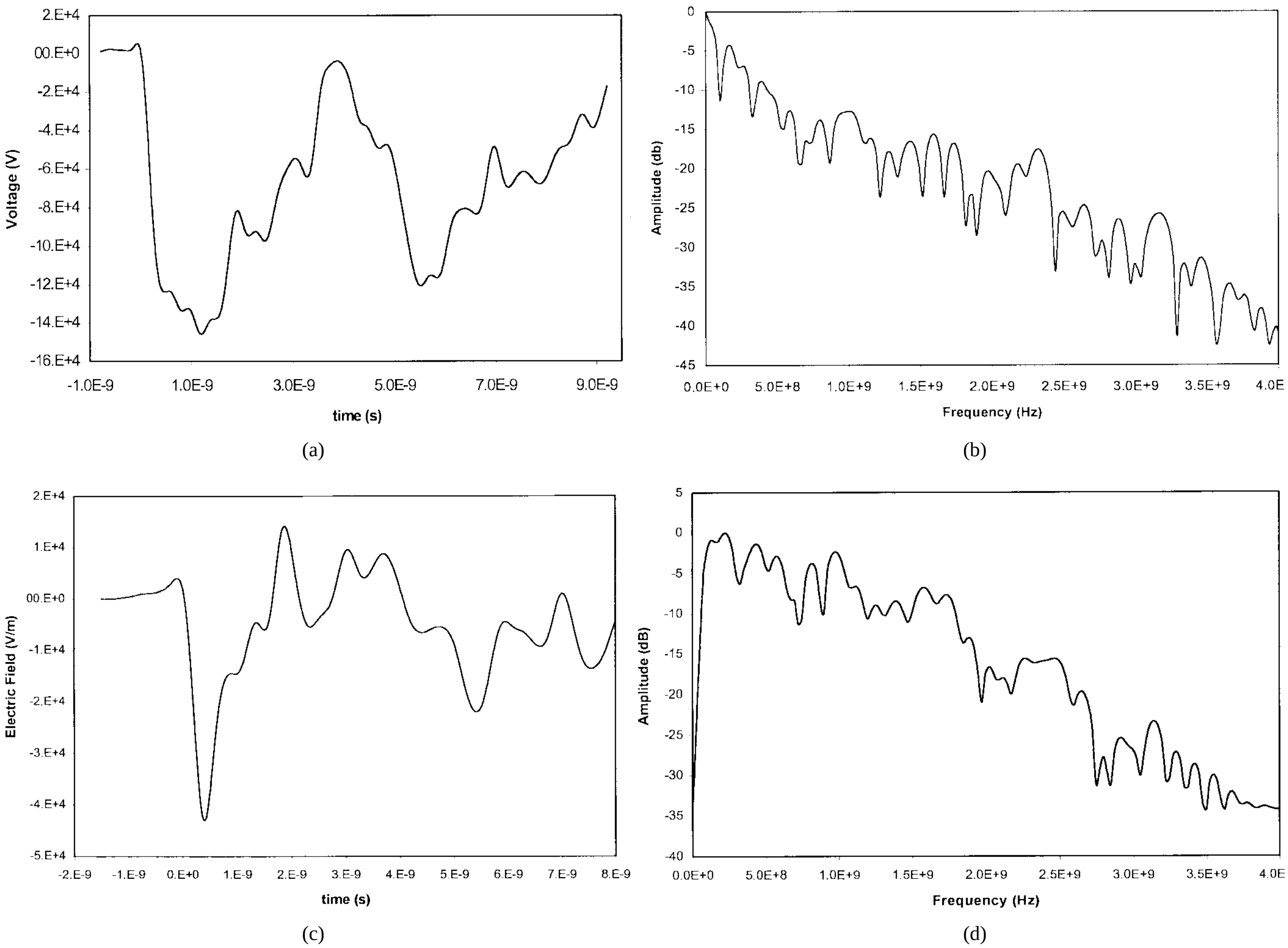

Fig. 7. Radiated field of the H-5 at 10 m with a large TEM horn.

a uniform electric field across the gap, are formed on an undoped, GaAs substrate surface. The AFRL 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 [43]. 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 2×10^6 shot life time in a 75-Ω resistively terminated, parallel-plate transmission line. 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-in GaAs substrate. The 0.25-cm gap has demonstrated hold off up to 32 kV, but a working potential of 20 kV is utilized for increased lifetime in a 75-Ω resistively terminated, parallel plate transmission line. The smaller gap reduces the rise time to 350 ps, reduces the voltage drop across the switch during lock-on to 1 kV, and four switches can be fabricated on a 2-in GaAs substrate, thus reducing cost. Recently, an array with a 30 cm $\times$ 30 cm aperture composed of a linear array of four flared TEM horns was designed, fabricated, and tested at the AFRL. Each 70-Ω 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 [44]. Further improvements in lateral-PCSS speed and voltage hold off will improve the range-field product of the array.

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 10 kHz, 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 [3].

C. Research Issues and Technical Challenges for Solid-State Switched Sources

The building and demonstration of advanced array designs will provide an increased understanding of the issues involved with timing of high power UWB signals. It is clear that improvements can be made in antenna design to enable the radiation over a wider spectrum compared to the relatively limited bandwidth of the dual finline antenna used in the GEM-series waveguide arrays. New designs that incorporate better elements and arrays that allow the late time energy to be radiated rather than being cut off. This will enable a more dynamic interaction of RF radiated pulses with scatterers, potentially obtaining more target response. It can also make applications from radar to electronic warfare more robust. Compact packaging will be accomplished for remote prospecting, airborne, and space applications.

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. Compact UWB antenna designs that preserve radiation efficiency and frequency spectrum are by far the greatest problem facing compact source design. The PCSS device will not survive a poorly designed pulse charging system or an inefficient radiating element. Great care must be taken to eliminate any excess energy, either stored or reflected, when the PCSS device is entering a high resistance, open switch state. Neglecting to consider stray energy in the system after a shot will severely shorten the life of the PCSS device.

IV. UWB ANTENNAS

A. UWB Antenna Design Considerations

For radiating or receiving UWB transients, we need antennas that are specifically designed and optimized for that task. Ordinary "wideband" antennas will generally not transmit fast transients because they have not been corrected for dispersion. As a result, there has been a considerable amount of research into fast transient antennas in the past five years. There are many articles and technical reports available now and more than a few very impressive antenna designs available. The IRA is one of the best [16]–[18], but there are others that are

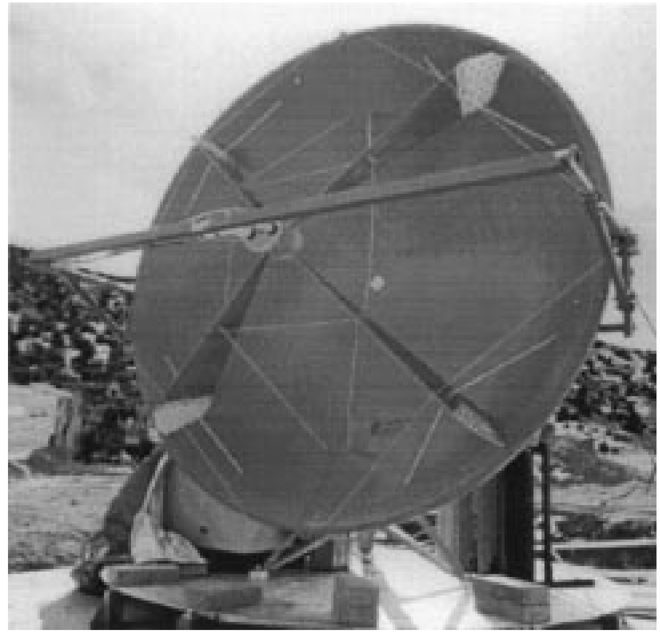

Fig. 8. The 4-m diameter reflector-impulse radiating antenna (IRA).

also exciting in terms of the potential for operating CW or with UWB transients.

An important consideration for transient antennas is minimizing both frequency and spatial dispersion. As demonstrated by Farr *et al*. [18], frequency dispersion is most easily overcome by a conical TEM horn or a biconic antenna, both of which are frequency independent structures which produce spherical wave fronts. However, because of the finite size of high voltage switches, it is often necessary to add some corrective lenses to the structure to optimize the quality of the spherical wavefront. The spatial dispersion caused by the nonplanarity of the wavefront can then be corrected with the use of a lens or a reflector. Both of these concepts have recently brought new standards of performance to the antenna world. A TEM horn with a polyethylene lens from SNL has been measured to emit a pulse with a FWHM of 23 ps [45]. Also, the team of Farr and Frost have recently built and demonstrated a 9-in diameter reflector IRA with a rise time of 25 ps, an improvement over the 18-in IRA which they had previously shown to radiate a pulse with a FWHM of 35 ps [46]. This corresponds to upper frequency limits of around 20 GHz.

B. Radio Frequency Lenses

As pulse rise times get faster, specifically $t_r < 250$ ps, we have found it necessary to include optics as well as antenna and transmission line theory in the designs of both pulsers and antennas. The materials most commonly used include polyethylene and polypropylene which have a relative dielectric constant near that of transformer oil $(\varepsilon_r = 2.3)$ and are thus optically compatible. Where there are interfaces between two different dielectric materials such as polyethylene and air, it is effective to use a Brewster angle to minimize reflections [47]. Notice in Fig. 6 that the Brewster angle appears as a curved surface since it was designed to match the spherical wavefront emanating from the throat of the horn.

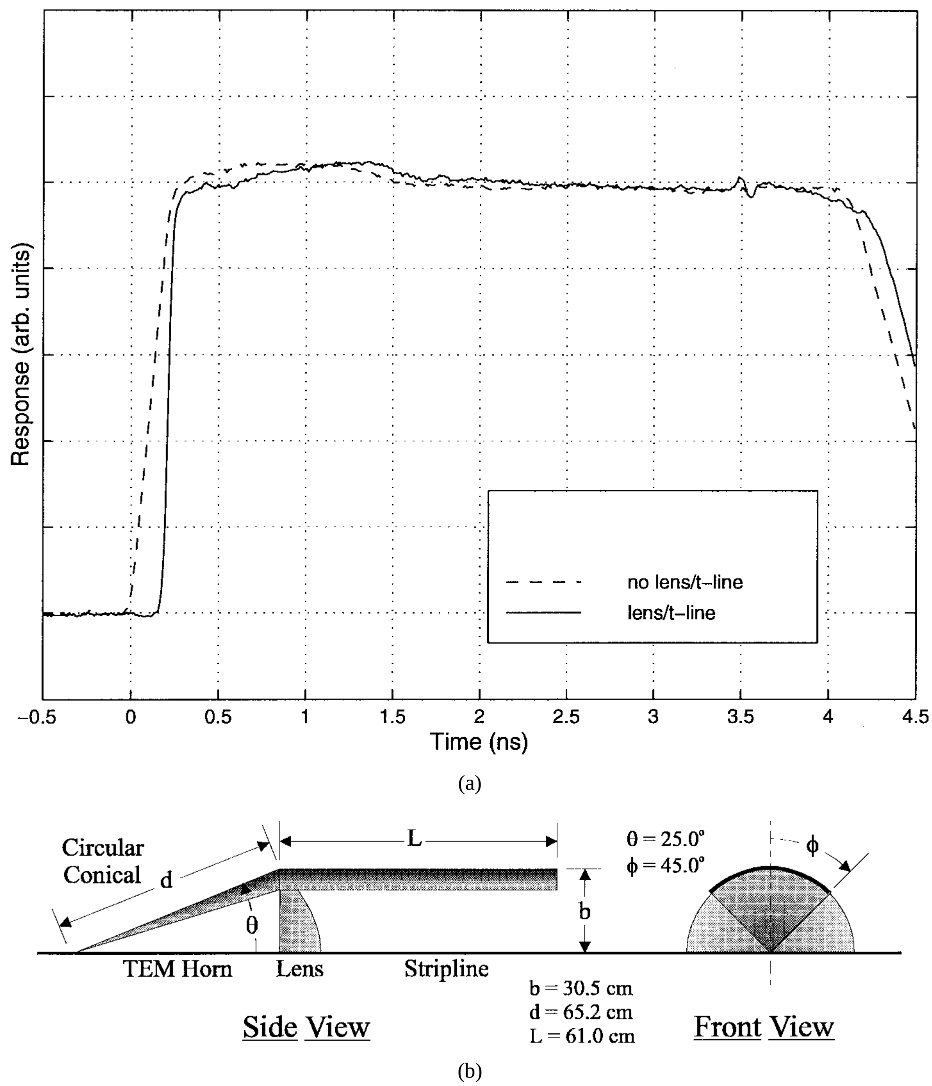

Fig. 9. Receive step response of a circular conical TEM horn with transmission line extension showing the improved rise time when the lens is included. Measured rise time is 50 ps with the lens and 200 ps without the lens.

At the AFRL, lenses have been used in several specific applications. In the IRA, a lens is used at the apex of the antenna to correct the astigmatism introduced by the finite size of the gas switch. With the lens in place, the wave is corrected to a near-perfect spherical wavefront so that upon reflecting from the parabolic surface, it emerges as a plane wave [48].

Focusing lenses are also used at the output of TEM horns to correct the nonplanarity of the wavefront (create a plane wave) and, in doing so, reduce the spatial dispersion which tends to limit the rise time. Fig. 9 shows measured receive step response of a circular conical TEM horn over a ground plane with an aperture radius of 30.5 cm. The lens diminishes the antenna's dispersion, improving its prompt response. The transmission line extension enables the sensor to accurately replicate the incident electric field waveform for a clear time of $2L/c$. The reciprocity principle implies the antenna, used in transmission and driven by step-function signals, radiate accurate impulsive fields for the same clear time. Fig. 10 is a picture a very fast horn filled with a solid dielectric which is shaped into a focusing lens at the output [46].

C. New Antenna Concepts

Sometimes, it is desirable to be able to change the beamwidth of an antenna. As a result, a new variation of the IRA has been created which has demonstrated that this is possible with a reflector IRA. Called the multipurpose IRA or MIRA, the design achieves the variation of the beamwidth by mechanically varying the position of the horn apex with respect to the focal point of the parabolic reflector [49]. Fig. 11 shows a drawing of the prototype MIRA that was demonstrated in the summer of 1997. The development is continuing. The next step will be to demonstrate that the beam can be steered by moving the apex from side to side with respect to the focal point

Bigelow *et al.* are developing graded dielectrics using mixtures of epoxy and TiO_2 which can be used to guide fast waves around bends without causing dispersion [50]. AFRL is also working on the development of artificial dielectrics in an attempt to reduce the weight of the lensing material [32].

Research in UWB antennas is beginning to have an effect in other areas of the electromagnetics world. The research

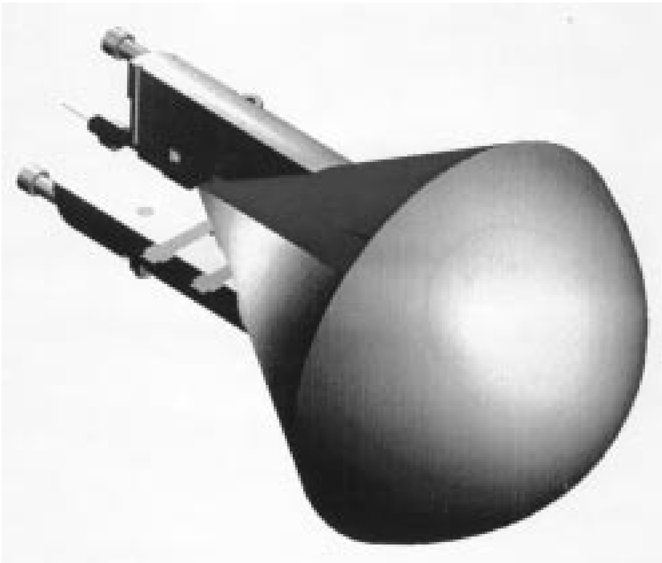

Fig. 10. Fast horn filled with dielectric.

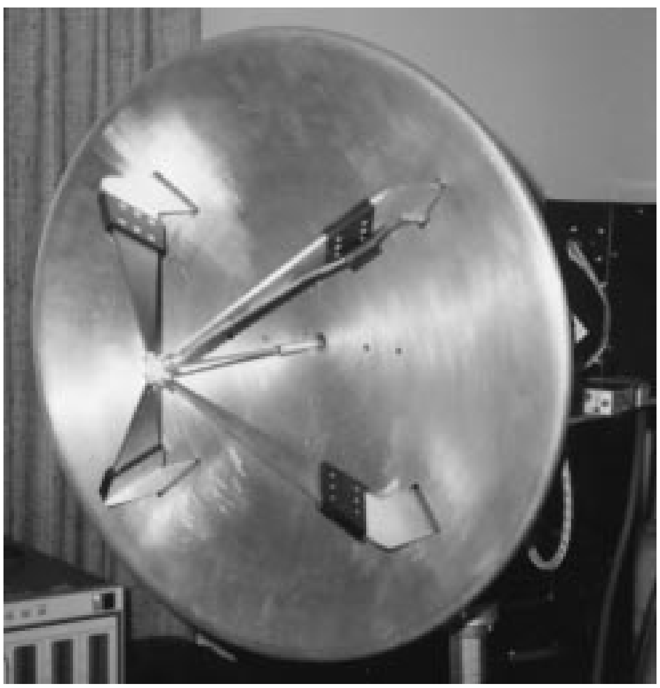

Fig. 11. Multifunction IRA.

into nondispersive, UWB antennas has made possible multiband antenna designs that offer up tantalizing possibilities for replacing several individual antennas with one multifunction antenna, thus reducing the space and weight. Likewise, the $\mathbf{p} \times \mathbf{m}$ concept, which increases the forward-directed, low frequency radiation from a small antenna, offers many exciting possibilities for reducing antenna size in air vehicles.

D. Technology Challenges in UWB Antennas

Several areas of antenna design offer challenges which must be tackled in coming years. An important one is that of making and demonstrating a compact array of TEM horns. While many strides in arraying of UWB antennas have been made to date, several characteristics remain to be examined such as the amount of cross coupling between antennas and switches and the effect it will have on switch and trigger circuit operation. Arrays driven by low-jitter, pulsed power sources such as photoconductive solid-state switches and small antennas with wideband characteristics are of interest.

Another exciting area of research is arrays of IRA structures. Theoretical considerations have indicated that such designs are feasible [51]. Such arrays would consist of many elements so that the voltage on any individual antenna is relatively small. Yet, the characteristic directionality of the IRA and the uniform response over an extremely large frequency range would be maintained. With a large number of antennas in the array, the signal received could be small, or, the transmitted signal large for the case of an active array. The “IRA Array” takes advantage of self-complementary principles (symmetry in design), aperture plane synthesis, and $\mathbf{p} \times \mathbf{m}$ resistive terminations to optimize the array’s low frequency response. An IRA array will make steerable UWB transient emitters a feasible technology for radar and other purposes that can be installed on ships, aircraft and spacecraft of the future.

V. Conclusion

In the last six years, there has been steady advancement in oil, gas, and solid-state switched UWB sources and related technology. We have developed a range of pulsers and antennas that enable us to provide a variety of energies, rise times, pulsewidths, and radiated waveforms that provide a flexible range of emission parameters available for experimentation. Table I indicates the range of this progress in terms of the figure-of-merit of the UWB source, defined as the peak electromagnetic field obtained in the far field, multiplied by the range at which the field was obtained. The figure-of-merit has units of voltage. Table I shows data from AFRL sources discussed in detail in this paper and from SNL [6]–[10], [52] and the Army Research Laboratory [53]. Table I also gives information about the antenna used and clarifying comments.

A portion of the research has reached for higher voltages and shorter rise times until we are now pushing the limits in material properties. In particular, the dielectric breakdown properties of insulating materials at these extremely high voltages and extremely fast rise times are being challenged. Likewise, with the fast rise times, we are now seeing the high frequency loss tangents of some materials show up where they were not a problem before.

The high voltage properties of insulators and the breakdown properties of gases and oils have not been systematically investigated and documented for very fast rise times. As a result, the data available is data gathered for a single engineering application. Generalized models and a thorough understanding of the physics do not exist. There is a limited database on liquid breakdown [11], [20], [54] that we plan to expand. Through the sponsorship of AFOSR, the AFRL and collaborating universities have begun a program to fill in this parameter space.

The future promises many more advances including the eventual realization of the full potential offered by our work in gas switched pulsers and novel antennas. The technology we have in hand can substantially increase the radiated field strength at range from these sources, as we combine more powerful and highest gain antennas.

Research into more capable photoconductive solid-state switches and UWB sources driven by them continues. The accomplishments to date by this class of UWB source encourages further work on switch lifetime and voltage performance.

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Forrest J. Agee (M'82–SM'91), for a photograph and biography, see this issue, p. 245.

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He was commissioned in the United States Air Force in 1962 and was stationed at the Air Force Weapons Laboratory from 1963 to 1967 and from 1968 to 1971. Since 1971, he has served as a civil servant with a position as Senior Scientist at what is now the Air Force Research Laboratory, Kirtland AFB, NM. He has coauthored the book, *Transient Lens Synthesis: Differential Geometry in Electromagnetic Theory* (Bristol, PA: Hemisphere, 1991) and co-edited another book, *Electromagnetic Symmetry*. He is founder and president of SUMMA Foundation, which sponsors various electromagnetics related professional activities including scientific conferences, publications, short courses, and awards. He has led an EMP short course and HPE workshops at numerous locations around the globe.

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He was with the Air Force Weapons Laboratory from 1970 to 1990, and the Air Force Phillips Laboratory from 1990 to 1997. He is currently the Team Leader of the Wideband Sources Group, Directed Energy Directorate, Air Force Research Laboratory, Kirtland AFB, NM. He has been active in electromagnetic interaction and coupling research, EMP simulation and testing, aircraft hardening design, design verification, and maintenance. He received special recognition from the Air Force for the development of hardness surveillance technology for use in aircraft assembly plants, maintenance depots, and operating bases. Since 1991, he has directed the development of high power Ultrawide Band Microwave sources and antennas for Phillips Lab. He has written numerous technical papers, MIL-STD's, journal articles, and book chapters on the subject of aircraft coupling, shielding, transient electromagnetics, and high power sources. He is a technical advisor to numerous U.S. government agencies on EM-related matters and represents the USAF in exchanging EM coupling and hardening information with NATO countries.

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Jane M. Lehr (S'90–M'94) was born in New York, NY, on August 25, 1963. She received the B.E. degree in engineering from Stevens Institute of Technology, Hoboken, NJ, and the M.S. and Ph.D. degrees in electrical engineering from Polytechnic University, Brooklyn, NY. During this time she was a Regents Scholar, a Polytechnic University Fellow, a Westinghouse Research Award Fellow and an AFOSR Scholar.

She worked at the High Energy Plasma Division of the Phillips Lab in 1992 and 1993 under the sponsorship of the Air Force Office of Scientific Research, where she aided in the development of a cool plasma working fluid for solid liner implosions. After working in both academia and industry, she joined the Wideband Sources Branch of Phillips Laboratory, now the Air Force Research Laboratory, Kirtland AFB, NM, in 1997. Her current research interests include pre-breakdown phenomena in liquids and gases, ultrawideband electromagnetics, transient phenomena in materials, and the generation, transmission and application of high power electromagnetic pulses.

James P. O'Loughlin (S'54–M'58) received the B.S. degree in electrical engineering from the University of Maine, Orono, in 1955, and the M.S. degree in electrical engineering from Northeastern University, Boston, MA, in 1959.

From 1956 to 1974, he was with Raytheon Company, first with the Power Tube Division and then with the Missile Systems Division, where he designed radar transmitters, magnetic amplifiers, and advanced systems. From 1974 to the present, he has worked at the Air Force Weapons Laboratory, now the Air Force Research Laboratory, Kirtland AFB, NM. His professional interests include power generation and conditioning, HPM and UWB source development. He has been instrumental in the design of the H-Series of UWB sources at AFRL.

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Jeffrey W. Burger was born in France in 1956. He received the B.S. degree in electronics and electrical engineering from the University of New Mexico, Albuquerque. He joined the Air Force Weapons Laboratory, now the Air Force Research Laboratory, Kirtland AFB, NM, in 1986, where he serves as a Senior Engineer with the Wideband Sources Group in the Directed Energy Directorate. His interests are in photoconductive switching as applied to high power microwave sources.

Jon S. H. Schoenberg (M'86) was born in Schenectady, NY, in 1963. He received the B.S. degree in electrical engineering from Cornell University, Ithaca, NY, the M.S.E.E. degree from Northeastern University, Boston, MA, and the Ph.D. degree in electrical engineering from the University of Colorado, Boulder, in 1985, 1989, and 1995, respectively.

From 1985 to 1989, he was assigned to the Electromagnetics Directorate of the Rome Air Development Center, Rome, NY, where he modeled FET's for MMIC's and performed high-speed photoconductive semiconductor switching research. In 1989, he joined the faculty of the Air Force Academy's Electrical Engineering Department, Colorado Springs, CO. In 1992, he joined the Quasi-Optical research group at the University of Colorado, where he developed microwave transmission-wave power combining arrays under an Air Force Institute of Technology fellowship. Since 1995, he has been assigned to the Directed Energy Directorate of the U.S. Air Force Research Laboratory, Kirtland AFB, NM, where he works on solid-state sources and antennas for ultra-wideband electromagnetic applications. His research interests include photoconductive semiconductor switching and time domain antenna array design.

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He was with the U.S. Air Force 6585th Test Group at Holloman AFB, NM, from 1981 to 1987. He joined the Air Force Weapons Laboratory, now the Air Force Research Laboratory, Kirtland AFB, NM, in 1987. His work at the Phillips Laboratory includes conducting gas and oil breakdown research and the design and development of ultra-wideband and narrow band microwave sources and pulser devices.

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He joined the Air Force Weapons Laboratory, now the Air Force Research Laboratory, Kirtland AFB, NM, in 1979 and is currently a Senior Engineer with the Wideband Sources Group in the Directed Energy Directorate. He has been active in electromagnetic interaction and coupling research and EMP simulation and testing. He is co-inventor of "Invention Disclosure: Power Enhancer for Solid State Switched Ultrawideband Array Transmitters," a novel technology application for economically and efficiently quadrupling the output power of solid state ultrawideband source modules.

John A. Gaudet (M'95) was born in Fitchburg, MA, in 1947. He received the A.B. degree in physics from the College of the Holy Cross, Worcester, MA, in 1969, the M.S. degree in physics from the University of Notre Dame, Notre Dame, IN, in 1971, and the Ph.D. in nuclear effects from the Air Force Institute of Technology, Wright-Patterson AFB, OH, in 1981.

He was commissioned in the U.S. Air Force following graduation from Holy Cross. During his 22-year career, he conducted research on numerical modeling of nuclear electromagnetic pulse, developed space experiments to study the effects of ionized plasma on satellites, and held several key leadership roles in pulsed power and high power microwave experiments. He was also an Associate Professor of Physics at the United States Air Force Academy, Colorado Springs, CO. Since 1993, he has held the position of Senior Research Scientist at the New Mexico Engineering Research Institute of the University of New Mexico, Albuquerque, working on a number of narrow band and ultra-wide band high power microwave projects with the Air Force Research Laboratory.