A Transient Array to Increase the Peak Power Delivered to a Localized Region in Space: Part I—Theory and Modeling

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***Abstract*—It is shown that an array of pulsed antennas (a transient array) can be used for providing a high concentration of electromagnetic energy into small regions. By controlling the timing of the pulses radiated from the individual elements, selected regions of space will see a coherent superposition of the radiated pulses forming "hot spots." The formation of "hot spots" is demonstrated by theoretical analysis. Using a highly damped sinusoid for the radiated pulse and dipole antenna elements, a contour plot of the peak electric field is determined for a linear array of six equally spaced sources. The impact of pulse-timing errors and the factors determining the size of the hot spot are also considered.**

***Index Terms*—Electromagnetic transient, focused array, hot spot, linear array, propagation, pulsed antenna, transient array analysis.**

I. INTRODUCTION

PROVIDING a high concentration of electromagnetic energy into small regions has applications in hyperthermia treatment of cancer and other maladies. A detailed discussion of the topic is provided by Durney and Iskander [1]. Producing a narrow-beam radiation in biological tissue requires a high-operating frequency with a wavelength that is small with respect to the target characteristic dimensions. However, the optimal wavelengths do not sufficiently penetrate the tissue to depths for effective treatment [1]. Consequently lower frequencies are used with less target discrimination.

Other applications for developing a high concentration of electromagnetic power include short-pulse radar and high-energy beams [2]. Several publications discuss the optimization of transient radiation through the control of the feed voltage [2]–[4]. Similarly, dipole arrays or transient arrays have been considered for optimizing the transient radiation [5]–[7]. Additionally, Schwartz and Steinberg [8] demonstrate that thinned transient arrays can achieve high resolution and low side radiation with a very few elements. Another approach uses focused aperture antennas [9]. Generally, these papers address the maximization of the transient radiated field at a specified time and far-field location. However, other desirable pulse properties may be optimized [10].

In this paper, an approach is presented for producing a high concentration of electromagnetic energy into small regions involving free space or nondispersive materials. The technique utilizes an array of ultra-wideband antennas radiating short duration pulses forming a transient array. It is shown that precise control of the time delays of the pulses radiated from the individual elements allows the concentration of energy within regions where the pulses may overlap in a coherent fashion. This approach is similar to using time delays for array beam steering [11], [12]. In fact, as the target area is moved away from the array into the far zone, the focusing of power into small regions degenerates into a beam-steering problem.

Recently, Funk and Lee [13] presented a study of beam steering for an array of ultra-wideband antennas. They show through theoretical analysis and measurement that precisely controlling the timing of pulses radiated from an array of N ultra-wide–band antennas produces a peak power that scales approximately as N^2 in directions where the pulses radiated from the individual elements combine coherently. Their work is extended in this paper to show how "hot spots" can be developed and controlled.

Although no measurement data are presented, a companion paper by the authors will present a hardware implementation of transient arrays for developing "hot spots" [14].

II. ANALYSIS

In order to demonstrate the formation of "hot spots" about an array of ultra-wide–band pulse sources, a very simple geometrical optics presentation is used. It is well known that the locus of points for a constant difference in time arrival of pulses from the two stationary omnidirectional point sources forms a hyperboloid of revolution where the sources are located at the foci of the hyperboloid. The theory of operation of the Long Range Navigation (LORAN) system is based on this concept. Consequently, for a given time delay between the two pulses radiated from fixed wideband antenna sources that are omnidirectional in a plane, a coherent overlap of the radiated pulses will occur at points that fall on a hyperbola as shown in Fig. 1. Note that for a specific time delay between the two radiated pulses, the coherent overlap occurs at points along only one of the legs of the

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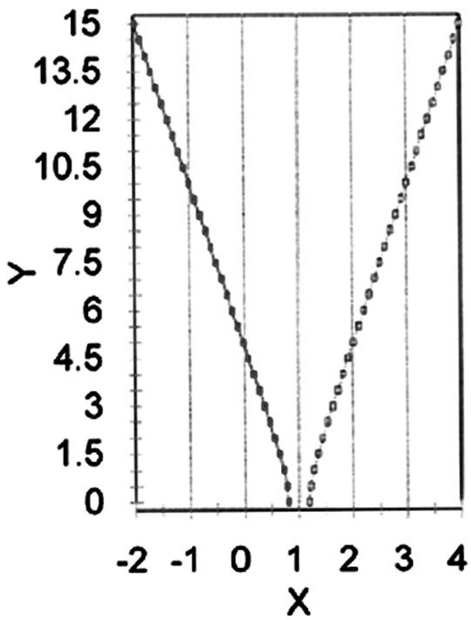

Fig. 1. A hyperbola with foci at (0, 0) and (0, 2). The mirror image about the x axis forms the other half of the hyperbola.

hyperbola. The other leg of the hyperbola represents the intersection of the two radiated pulses for a "negative" delay, where the time delay between the pulses has been reversed.

A. Coherency Requirements

Now increase the number of sources from two to three and look for a coherent combination. Clearly, one should consider only two sources at a time in looking for coherence. The total number of hyperbolas will be the combination of the number of sources taken two at a time, i.e., the binomial coefficients

$$C(N, M) = \frac{N!}{M!(N-M)!} \tag{1}$$

where $M = 2$ and N is the number of sources. However, only $N-1$ hyperbolas are independent. For three sources, there will be a total of three hyperbolas with only two hyperbolas needed to establish the common coherency point, where the three hyperbolas have a common intersection point. Actually any two of the three hyperbolas can be used to establish the common coherency point for three sources.

The region in proximity to this coherency point will be a "hot spot." The size of the "hot spot" region will depend upon the duration of the radiated pulse among other factors. Note that there is no requirement on the placement of the sources. However, for the study presented in this paper only a linear array of sources is considered. Extending this study to curvilinear arrays is straightforward.

Without loss of generality for a linear array, sources are considered to be located along the x axis of a Cartesian system (see Fig. 2). The general equation for the hyperbola describing the locus of points for a constant difference in time arrival from two of the sources is

$$\frac{(x-\overline{x}_{\text{on}})^2}{a_n^2} - \frac{y^2}{c_n^2 - a_n^2} = 1 \tag{2}$$

where

$$\overline{x}_{\text{on}} = \frac{x_n + x_o}{2} \tag{3}$$

and

$$c_n = \frac{x_n - x_o}{2}. \tag{4}$$

Here $x_n = 0, 1, 2, \ldots, N-1$, is the x coordinate of the nth source and $2a_n$ is the propagation path difference from the source at x_o and the source at x_n which are located at the foci of the hyperbola.

For a given target location (x, y), it is straightforward to determine the propagation path lengths to the target location. For the sources located at x_o and x_n, the difference in the propagation path lengths is (see Fig. 2.)

$$2a_n = \sqrt{(x-x_0)^2 + y^2} - \sqrt{(x-x_n)^2 + y^2}. \tag{5}$$

The foregoing procedure can be repeated until all N sources have been considered.

In order for the transmitted pulses from the array elements to add coherently at the target location, the timing of the sources must be adjusted to compensate for the differences in the propagation path lengths. If the propagation path from the nth source is less than the path from the oth source, i.e., $a_n > 0$, then the pulse radiated from the nth source must be delayed by Δt_n, where

$$\Delta t_n = 2\frac{a_n}{c} \tag{6}$$

and c is the propagation speed in the ambient medium. On the other hand, when the propagation path from the nth source is greater than the path from the oth source, i.e., $a_n < 0$, then the pulse radiated from the nth source must be timed to occur before the oth source pulse excitation by the time interval Δt_n.

For the data shown in Fig. 1, the sources are located at $x_o = 0$ and $x_1 = 2$ with the target located at (3, 12). Accordingly, from (3)–(5), $\bar{x}_{01} = 1, c_1 = 1$ and $a_1 = 0.163\,861$. Using these parameters in (2) yields the hyperbola shown in Fig. 1.

B. Pulse Radiation Considerations

The analysis presented up to this point has not considered the individual radiation patterns of the array elements. Consequently, in order for the foregoing to remain valid for directive elements or at least to provide maximum effect, each element must be oriented so that the target is located along the boresight. Another important consideration for pulse radiation is the antenna bandwidth. For example, in their study of beam steering of ultra-wideband radiation, Funk and Lee [13] used bow-tie antenna elements. Samaddar and Mokole [15] consider a variety of antennas for ultrawideband radiation and Giri [16] analyzes the resistively loaded biconical antenna for ultra-wideband applications. The general topic of designing antennas for pulse radiation is presented by Tesche [17]. In the presented study, an array of electrically-short dipole antennas is used to form a transient array.

For elements that are omnidirectional in the plane defined by the linear array and the target, electronic focusing is feasible as demonstrated by Funk and Lee. The primary difference between

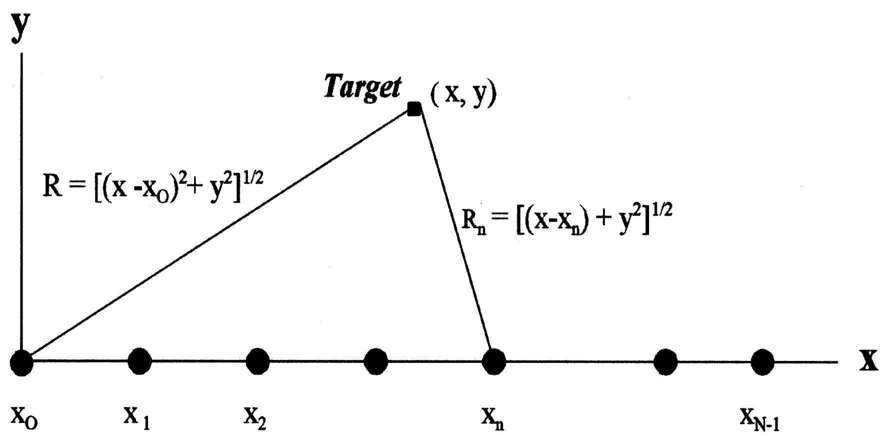

Fig. 2. An illustration of a line of N sources placed along the x axis with a specific target located at (x, y).

their study and this paper, is that the Funk and Lee paper concentrated on distant radiation where the distance to the target is large when compared to the maximum linear dimension of the array, and where the hyperbolas are asymptotically approaching parallel straight lines in the direction of maximum radiation.

For the analysis of pulse radiation from a linear array, certain simplifying considerations are made. It is assumed that the separation between elements is sufficient, that multiple scattering effects as well as mutual coupling between elements may be ignored, and that the elements may be considered individually. Accordingly, the radiated electric field from each element in the array may be expressed in terms of the element effective length as a function of frequency [18], [19]

$$\vec{E}_n(\vec{r},\omega) = j\frac{\omega\mu}{4\pi}\,\vec{h}_{\rm en}\,I_n(\omega)\frac{e^{-jkr}}{r} \tag{7}$$

where $\mu = \mu_o = 4\pi \times 10^{-7}$ H/m is the magnetic permeability of the ambient medium, I_n is the terminal current in the nth element, r is the radius vector from the nth element, $\vec{h}_{\rm en}$ is the effective length of the nth element, $\omega = 2\pi f$ is the radian frequency, $k = \omega\sqrt{\mu\varepsilon}$ is the propagation constant in the ambient medium with dielectric permittivity ε, and finally $j = \sqrt{-1}$. For a dipole antenna the effective length is

$$k\,\vec{h}_e \approx 2\frac{\cos(kh\cos\theta) - \cos(kh)}{\sin(kh)\sin\theta}\,\vec{a}_\theta \tag{8}$$

where θ is the polar angle measured from the axis of the dipole and $\vec{a}_\theta$ is the spherical coordinate unit vector associated with the polar angle [18], [19].

To obtain the radiated pulse, Fourier frequency superposition (Fourier Transform) is used. Of course this requires knowledge of $I_n(\omega)$ which in turn requires the solution of the circuit problem represented by the attachment of the pulser to the antenna terminals. Generally, the circuit problem can be solved if the Thevenin equivalent parameters for the antenna and pulse source are known. These parameters may be measured or calculated.

Because the effective height of the dipole antenna has transcendental dependence on frequency, the radiated pulse is expected to be very much different in shape from that of the input current. However, if the dipole is electrically short, i.e., $kh \ll 1$, as the antenna elements used by Funk and Lee [13], then $h_e \approx h$ independent of frequency and (7) yields

$$\mathcal{E}_n(r,t) \approx \frac{\mu h}{4\pi r}\frac{\partial}{\partial t}\mathcal{J}_n(t)\,|_{t-r/c} \tag{9}$$

where

$$E_n(r,\omega) = \int_{-\infty}^{\infty} \mathcal{E}_n(r,t)\exp(-j\omega t)\,dt \tag{10}$$

and

$$\mathcal{J}_n(r,t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} I_n(r,\omega)\exp(j\omega t)\,d\omega \tag{11}$$

are Fourier Transform pairs [17]. Other wideband antennas are available and will be considered in future studies. According to (9), the radiated electric field pulse from an electrically short dipole antenna is directly proportional to the time-delayed time derivative of the antenna terminal current and inversely proportional to the distance from the antenna element.

Many other ultra-wideband antenna elements could be used in the concentration of electromagnetic energy. In a companion paper the authors use resonant thick dipoles for the array elements to perform measurements on the formation of "hot spots" [14]. The thick dipole elements under impulse excitation radiate highly damped sinusoidal pulses [20]. Consequently, the computations presented in this paper will assume highly-damped sinusoids for the radiated pulses.

C. Total Radiated Power

The radiated power density may be determined by using the Poynting vector and the principle of superposition. The total electric and magnetic fields from N sources is simply the vector addition of the field vectors produced by each source. Therefore, the total radiated power density is

$$\vec{\mathcal{P}}_{\rm total}(\vec{r},t) = \sum_{n=0}^{N-1}\vec{\mathcal{E}}_n(\vec{r},t) \times \sum_{n=0}^{N-1}\vec{\mathcal{H}}_n(\vec{r},t) \tag{12}$$

where $(\vec{\mathcal{E}}_n, \vec{\mathcal{H}}_n)$ represent the instantaneous electric and magnetic field vectors produced by the nth source. Note that (12) provides the total power density at the point located by the radius vector r and at the time t.

According to (12), the total radiated power at the coherency point may be increased by a factor approaching N^2 for N

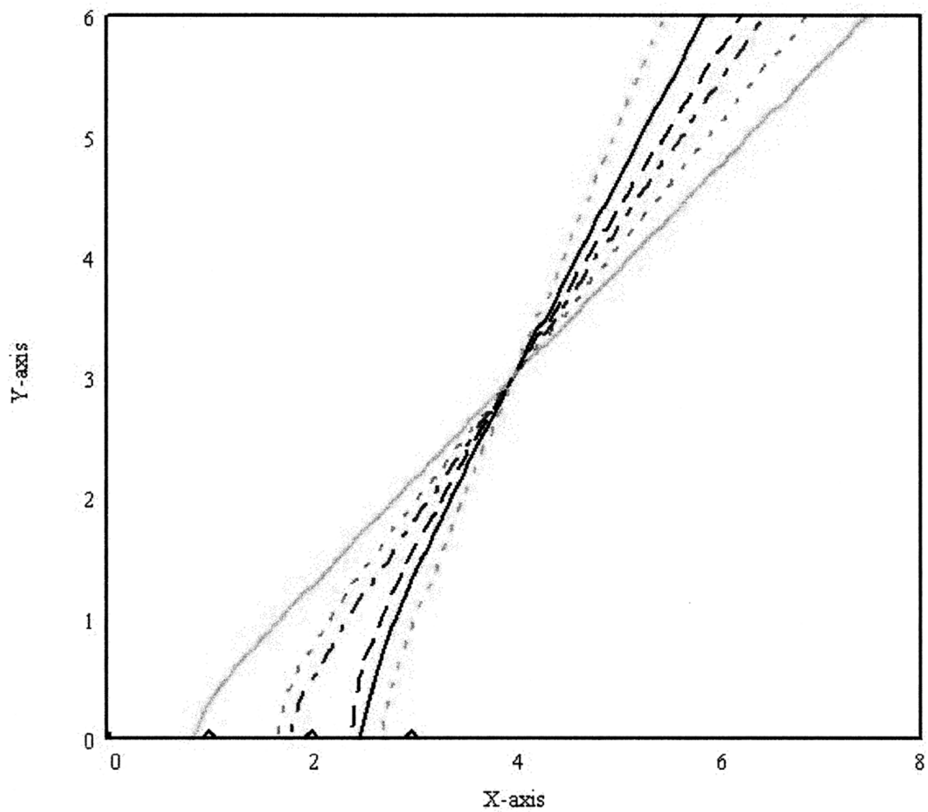

Fig. 3. The hyperbolas obtained from four sources located at $x = 0, 1, 2$, and 3 with a target located at (4, 3).

sources. However, the actual total radiated power at the coherency points will depend upon the vector sums shown in (12).

D. Numerical Modeling

To fully understand the formation of the "hot spot" a simple two-dimensional (2-D) numerical model was developed. The model assumes a known and identical pulse shape is radiated by each element of the array and uses the radial attenuation as shown in (7). In addition, the elements of the array are considered to be omnidirectional in the plane of the analysis. The time history of the electric field is computed at field points by the superposition of the pulses from the individual elements of the array considering the radial attenuation, and the time lag associated with the propagation distance from the radiating element to the field point.

The area in front of the linear array is divided into grids and the electric field time history at each grid point is systematically constructed. After the peak field strength is determined at each grid point, a contour plot or surface plot is constructed presenting the peak-electric field as a function of position in the 2-D area under investigation. Of course, the time history of the electric field will vary considerably across the grid. However, inside the "hot spot," the total electric field will have a time dependence very similar to the radiated pulse from each element but with an amplitude N times greater.

This simple numerical model has been validated experimentally. The authors will present the results of that experiment in another paper[10]. Having a simple model will enable the investigation of the effects of range, pulse width, jitter, etc., on the formation of a "hot spot."

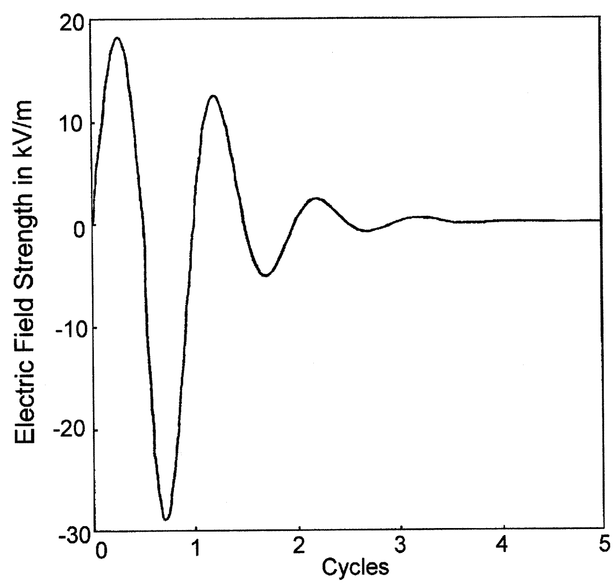

Fig. 4. An illustration of the radiated pulse from a broadband thick dipole antenna that is resonant at 150 MHz and is driven from an impulse source.

III. Results

To illustrate the technique for producing a high concentration of electromagnetic energy, a transient array of thick dipole antennas array is considered. The antenna sources are located at $x_n = n$ meters, $n = 0, 1, 2, 3$ and the target is located at (4, 3). Using (2)–(5) the parameters required for focusing may be determined. The source at the origin is used as a reference and (5) is used to obtain the propagation path length differences for

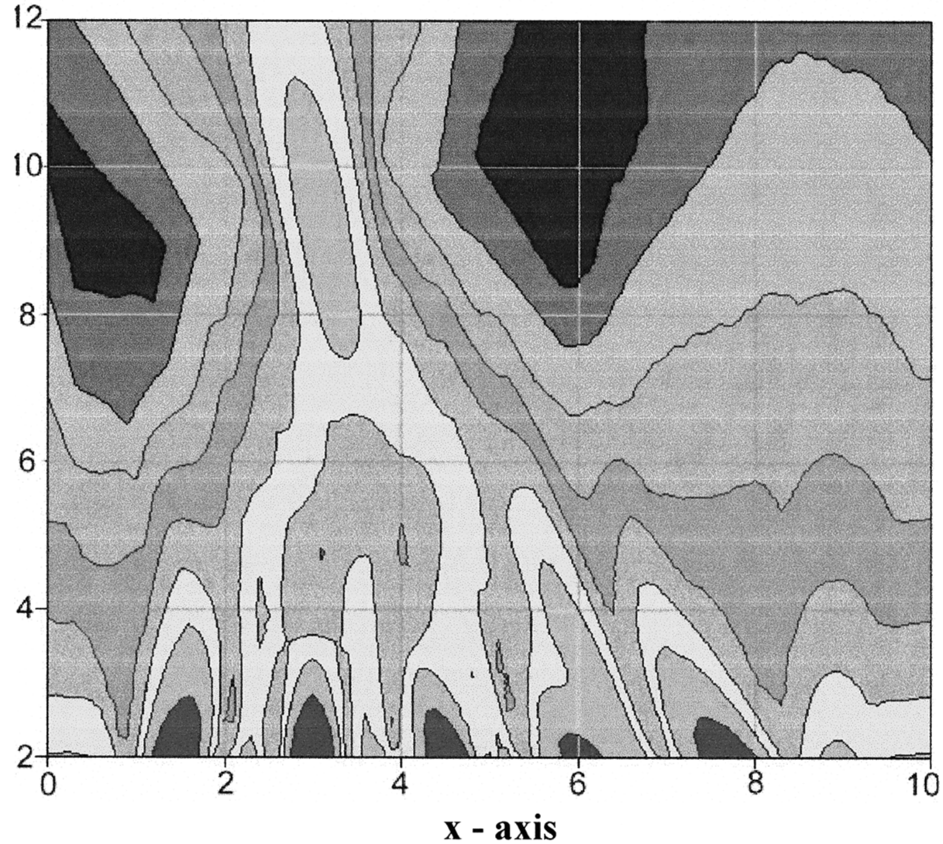

Fig. 5. A 3-dB contour map of the peak electric field for sources located at $x = 0, 2, 4, 6, 8$, and 10, with the target located at (3, 10). The radiated pulse shape for these data is shown in Fig. 4.

each of the other three sources. With these parameters a maximum set of six hyperbolas are obtained to illustrate the coherence points as shown in Fig. 3. As expected, all six hyperbolas intersect at the target coordinates (4, 3). Note that no other intersection points are observed. At the target location the peak electric field should be about three times ($+9.5$ dB) the field strength from a single radiator.

In order to examine the size of the "hot spot," a realistic radiated pulse, a highly damped sinusoid, is considered (see Fig. 4). Each of the sources is assumed to be producing the radiated pulse shape shown, where the electric field peak amplitude for all pulses is normalized to 1 V/m at 1m distance from the antenna. In order to use (9) to compute the radiated pulses that focus at the target, (6) is used to obtain appropriate delay times for the individual sources. For an array of six sources at $x = 0, 2, 4, 6, 8, 10$ and a target located at (3, 10), the following results are obtained for the source delay times:

$$c\Delta t = \begin{bmatrix} 0.3904 \\ 0.3904 \\ 0 \\ -0.7400 \\ -1.766 \end{bmatrix}. \tag{13}$$

Accordingly the contour map shown in Fig. 5 is obtained.

The data in Fig. 5 indicate a complex pattern of radiation is obtained with focusing at the target clearly occurring. Calculations have revealed that the elongation of the hot spot is dominated by the distance of the target region from the array. As the target approaches the far zone of the array, the elongation approaches a beam. The width of the hot spot appears to be strongly dependent upon the pulse width/characteristic wavelength.

To demonstrate the effect of combining waveforms in a region of space, two scenarios are presented. Both scenarios use a six-element array where the elements are separated by characteristic wavelengths of the pulse shown in Fig. 4. In the first scenario [Fig. 6(a)], there is no time delay between sources (i.e., $\Delta t = 0$). In the second scenario, [Fig. 6(b)], the time delays have been adjusted to focus on a region near the array. The results are visually dramatic. Simply by making a small timing adjustment, the peak power delivered to the target region increased significantly.

Since some jitter in the firing of the pulse sources is expected, the effects from timing errors should be studied. An example of the result of timing error is shown in Fig. 7. Here the radiated power density is shown for three conditions—a single pulse (see Fig. 4), two pulses in coherence and two pulses with a small-timing error. Note that a small-timing error (one tenth of the characteristic oscillation cycle) reduces the peak radiated power density by about 10%. Fig. 8 provides the peak radiated power density for two pulses (see Fig. 4) with a continuous increase in timing error. Here it is noted that a timing error of about 30% reduces the peak power by about 3 dB.

As expected, the hot spot will eventually disappear as the jitter error is increased. However, calculations indicate that the hot

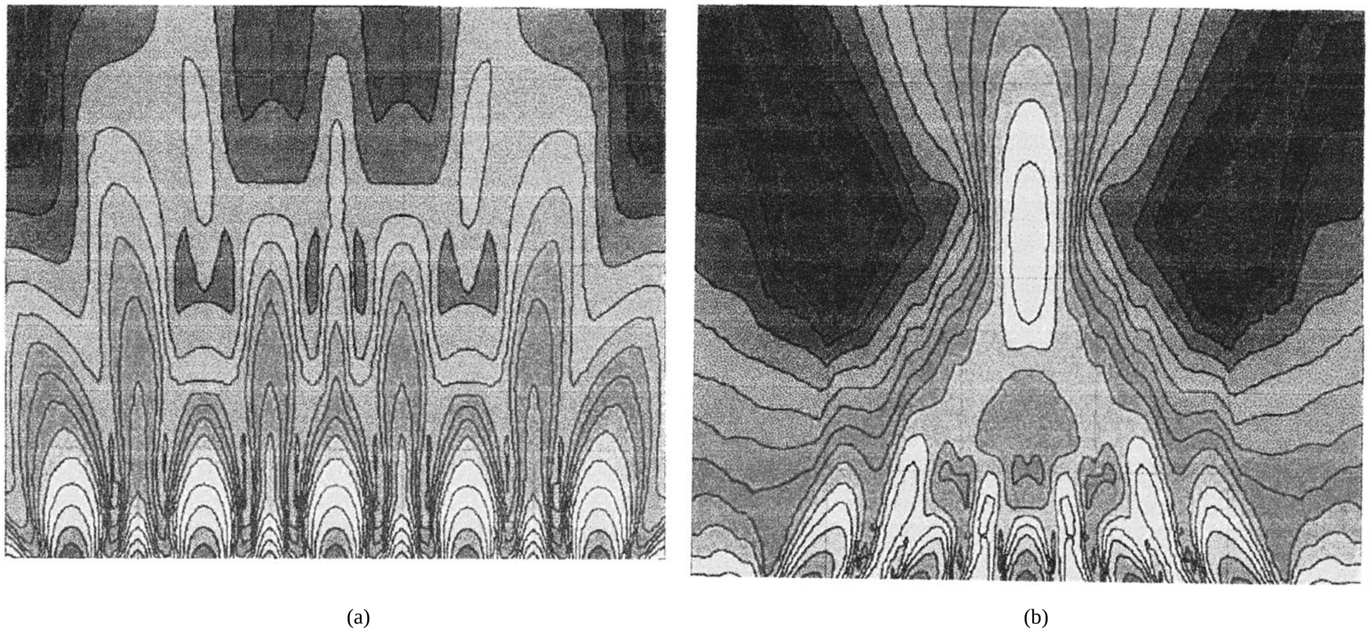

Fig. 6. (a) The Contour map of the peak electric field for a six-element array with no time delays between the radiated pulses. (b) The contour map of the peak electric field for a six-element array with time delays to produce a "hot spot."

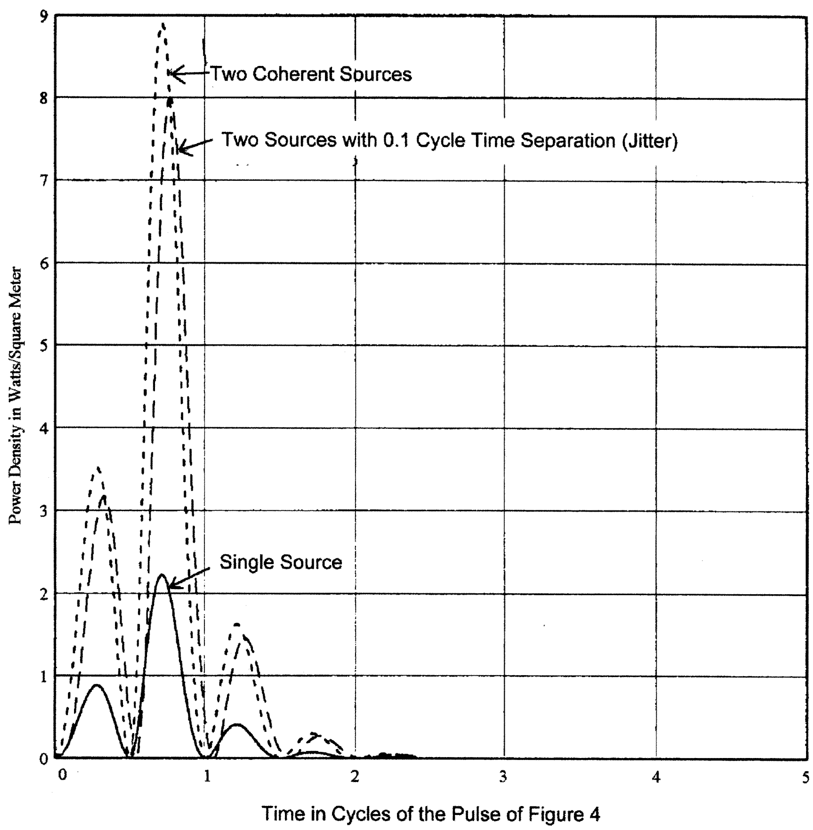

Fig. 7. An illustration of the radiated power density for two-pulse sources combining coherently and noncoherently.

spot will continue to exist at the target location with as much as 30% jitter in the firing of the pulsers.

IV. Conclusion

It has been shown that a high concentration of electromagnetic energy can be accomplished by using an array of ultrawideband pulse radiators. Controlling the timing and the duration of the pulses can lead to the formation of localized "hot spots," where the pulses from the individual elements combine coherently. The location of the hot spot is determined by the timing of the radiated pulses and the size of the hot spot is primarily determined by the duration of the pulses. With an array

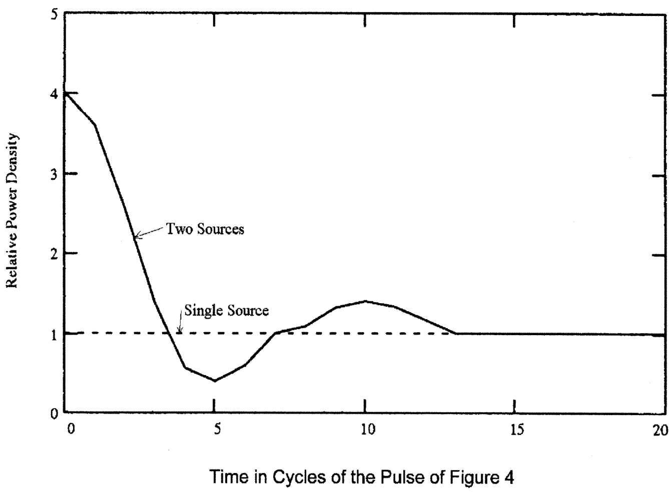

Fig. 8. An illustration of the timing error on the combination of pulses from two sources.

of six elements, it is shown that a "hot spot" is formed with a radiated power density that is increased by 15.6 dB above that of a single element. It is further shown that a 30% timing error may reduce the peak power by about 3 dB.

For biomedical applications, a six-element array may be used to focus electromagnetic power into a small region. However, some dispersion is expected which will increase the pulse width within the biological material and thereby reduces the size of the hot spot. This is a topic that is reserved for future study.

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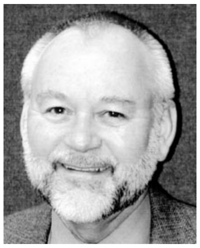

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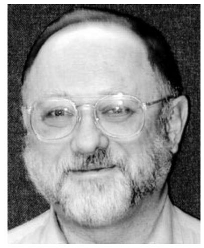
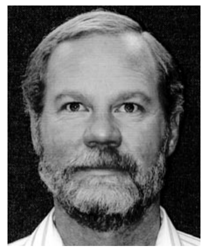
Dr. McLemore is a Member of Sigma Pi Sigma, Tau Beta Pi, Sigma Xi, and NARTE. From 1996 to 1997, he was Chairman of the Albuquerque joint IEEE chapter of EMC, MTTS, NPS, and APS. From 1998 to 1999, he was Chairman of the Albuquerque IEEE Section. He is a Member of the Union of Radio Science International (URSI), Commission E, and is currently the Chairman for the National EMC Society Technical Committee 5 (TC-5), High-Power Electromagnetics.



Harald Dogliani received the from the B.S. degree in physics from the United States Air Force Academy, Colorado Springs, CO, in 1964, where he received the O.J. Squire award for the outstanding cadet in physics. He received the Ph.D. degree in physics from the University of Colorado, Boulder. He has more than 30 years of experience in directed energy applications including lasers, particle beams and high-power microwaves. Currently, he manages special projects at the Los Alamos National Laboratory.



William A. Walton, III received the B.S. degree in electrical engineering from the University of New Mexico, Alburqurque, in 1977.

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