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COHERENT POWER COMBINING OF ULTRA-WIDEBAND PULSED RADIATION IN FREE SPACE

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ABSTRACT

Photoconductive switches are used to trigger an array of three pulsed ultra-wideband antennas. The jitter-free pulses radiated by each antenna add together in free space to produce a radiated field pattern that is steerable via true optical time-delay techniques. This technique can be applied to an N-element phased array for increased radiated power and beam-steering capabilities.

INTRODUCTION

Photoconductive (PC) switching has received intense interest recently as a means of producing high-power ultra-wideband (UWB) microwave pulses [1-2]. Much emphasis has been placed on using a single PC switch to generate and radiate high peak powers [3]. As a result of this emphasis, the PC switch is often operated at its maximum hold-off voltage [4], resulting in potentially damaging filamentary currents when the switch is closed. Not only does this drastically reduce the PC switch's lifetime, unreliable performance can result from such a scheme, because of the resulting high degree of pulse-to-pulse variation.

Our approach, however, has been to exploit the jitter-free nature of photoconductive switching. When operated at more modest hold-off voltages, GaAs and Si PC switches exhibit jitter-free (subpicosecond) operation with respect to a laser trigger pulse. Hence, it is possible to radiate high-power pulses by synchronizing an array of radiators, each driven by an individual PC switch. The electric field from each of the synchronized radiators adds together in free space, giving a peak power that scales as N^2, where N is the number of radiating elements. This approach allows each PC switch to be operated at safe power levels, where the performance of the PC switch is not expected to degrade over time. Furthermore, this technique allows the creation of a UWB phased array, whereby the antenna array radiation pattern can be controlled by adjustment of the arrival time of the optical pulse, which triggers each element (true time delay). In this paper, we present the first demonstration of the coherent addition of UWB pulsed radiation in free space from three bowtie antennas, each driven by an Si PC switch. An optical true time delay has been successfully used to steer the radiated beam.

EXPERIMENTAL RESULTS

Figure 1 shows a detailed view of the three Si PC-switch-driven UWB bowtie antennas and their orientation with respect to the UWB field sensor. The optical system (not shown) consists of a compact, diode-laser pumped, mode-locked Nd:YLF laser and regenerative amplifier. The regenerative amplifier delivers a 540-Hz train of 5-μJ pulses of 120-ps FWHM (full width at half maximum), at a wavelength of 1.054 μm. The drive frequency is maintained in synchronization with the laser cavity round-trip time via an active computer-controlled stabilization system.

Three identical bowtie antennas were fabricated on copper-clad glass/epoxy circuit boards with a thickness of 1.55 mm by the use of a standard photosensitized etching technique. The antennas were designed to radiate an approximately 250-ps FWHM pulse in response to step-function electrical excitation. Hence, no attempt was made to provide resistive loading [5], which would defeat the "derivative" properties of the bowtie. As shown in Fig. 1, a bowtie of length $b = 5.7$ cm and $\beta = 29°$ was used. The individual elements were separated by $d = 10$ cm. An Si PC switch with a 1-mm gap size was electrically connected to the apex of each bowtie with copper foil and silver paint. The Si switch acts as a fast-closing (<<1 ns), slow-opening (on the order of microseconds) switch, providing a steplike electrical excitation to the antenna.

The bottom and top halves of each antenna were pulse charged with opposite polarity to the charge voltage, $V_a = 410$ V, through a 1-kΩ resistor and in synchronization with the 540-Hz optical pulse train that was focused onto each gap. The laser beam used to trigger the PC switches was split into three beams by a system of half-wave plates and polarizing beam splitters. The optical beam path to two of the three elements included an adjustable time delay that uses prisms mounted on precision translation stages. The three individual laser beams were focused onto the PC switch gap. A short conical monopole antenna (CMA) with $a = 1.3$ cm and $\alpha = 47°$ (see Fig. 1) was used as a field probe. The CMA was placed 1 m from the plane of the circuit board at an angle of θ in order to monitor the field that was transmitted through the glass/epoxy board. The electric field can be determined within a few percentage points from the integral of the received signal [6], provided that the spectral content of the field is primarily below 2 GHz ($\lambda = 15$ cm, $ka = 0.5$, where k is the wave number), which in this case is true.

We verified the bowtie antenna design and radiation pattern by feeding the antenna with a 50-Ω transmission line and performing time-domain reflectometry (TDR) and time-domain transmission (TDT) measurements. The TDR measurements indicate that, to first order, the bowtie can be regarded as an open-ended transmission line with a round-trip time of 530 ps. The TDT measurements revealed that the radiated field of a single element exhibits no noticeable dependence on θ at the frequencies detected by the CMA field probe. Measurements on a single optically triggered bowtie also verified this symmetry.

Each bowtie antenna radiates a 267-ps FWHM pulse closely corresponding to half a round-trip time as measured by TDR. At a far-field observation point, the relative time it takes for a radiated pulse to get from each of the elements to the field probe depends on θ. For a given angle, we can adjust the relative triggering time of each of the bowtie elements so that the pulse from each of the three elements arrives simultaneously for observers at that angle. For instance, in one of our experiments, each of the three elements is triggered with a relative delay of 160 ps between adjacent elements; the fields from each of the elements should add together in free space at 30° to produce a signal at the field probe three times as large and, hence, a received peak power nine times as large. In the actual experiment (Fig. 2), the charge voltage V_a drops when additional elements are added, because of the high output impedance of the pulser; hence the peak signal received is scaled by a factor of 2.3 over that obtained by a single element, rather than by a factor of 3.

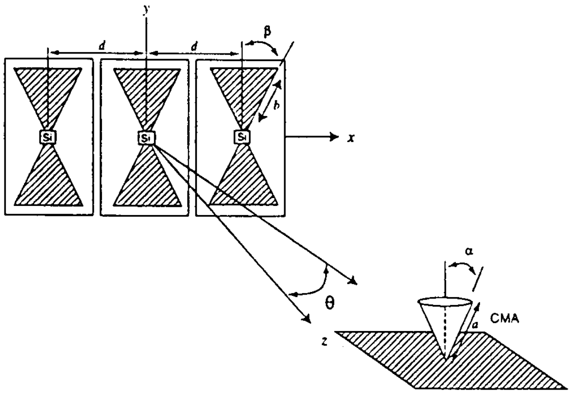

Figure 1. Schematic diagram of experimental setup showing spatial relationship between three bowtie antennas and conical monopole antenna (CMA) field probe. Arrival time of optical pulses at two leftmost antennas is controlled by true optical time delay, as described in text. CMA distance from antenna plane is 1 m.

As shown in Fig. 3, as we move away from 30°, the received pulse broadens and decreases in amplitude as the pulses from the three elements no longer arrive simultaneously. Although terms such as *beam solid angle* and *directivity* are not particularly meaningful when applied to a pulsed base-band signal like this one, we can define a beam width in terms of the half-peak-power points.

In Fig. 4 we plot the peak power versus angle for the case of no delay between elements and for the case

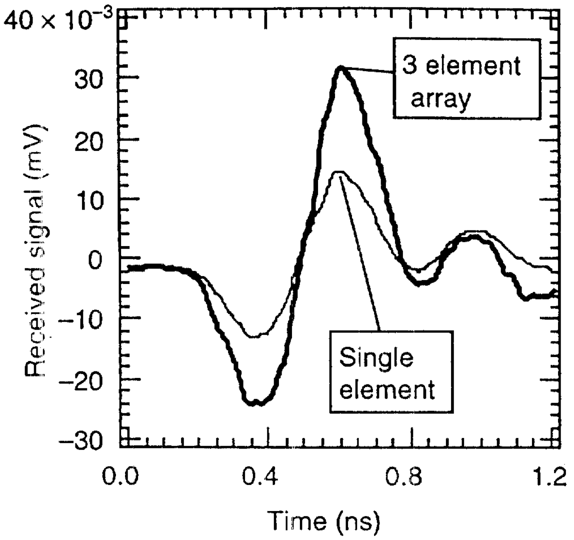

Figure 2. CMA response showing received waveforms at $\theta = 30°$ and relative delay of 160 ps between adjacent elements. Optical trigger is blocked to all but one of bowtie antenna elements (single element), and all three antennas are simultaneously activated (array).

with a delay of 160 ps between adjacent elements. A fit to a Gaussian pulse profile is shown for each case with a beam width of 20° for both. With 0-ps true time delay between elements, we note that the beam points toward 0° (broadside). Although the theoretical pointing angle for the 160-ps delay is 29°, we measure the largest peak field at 40° with measurements made in 10° increments. This discrepancy may be due to a number of variables, but most importantly that the measurements were not performed in an anechoic chamber. Hence, interference from objects in the laboratory may have some effect on the amplitude and shape of the received pulse. In the future, we plan to complete measurements within an anechoic chamber.

CONCLUSION

Although a three-element system was used here, this technique is equally applicable to an N-element array. In theory, the peak radiated power will scale as N^2 because of the coherent addition of electric fields. In practice the radiated power will be somewhat less, because of the decrease in optical energy used for triggering each element. The implementation of an N-element jitter-free array for free-space power combining to increase the radiated power is perhaps a more viable solution to power scale-up than the use of a single PC switch forced to handle large and potentially damaging currents. In addition, the array provides beam-steering capabilities not available from a single switch/antenna system. The UWB pulses are radiated in complete synchronization with the optical pulse train, a property that can be exploited in the design of coherent receivers. Hence, arrays of PC-switch-driven UWB antennas can be devel-

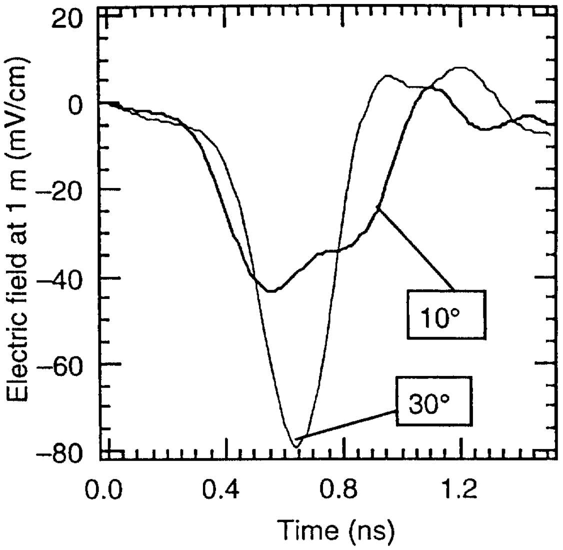

Figure 3. Field received at various angles with relative optical trigger delay of 160 ps between adjacent antenna elements.

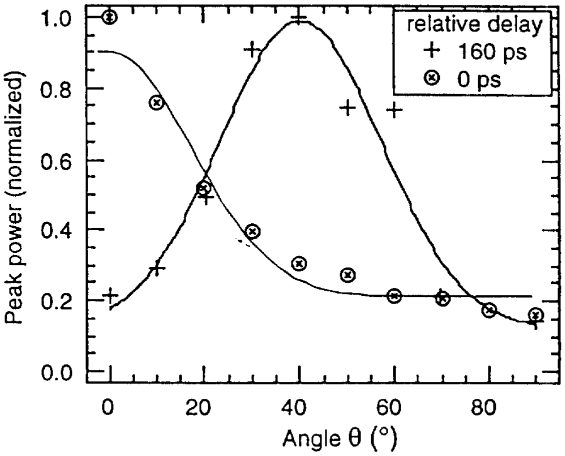

Figure 4. Peak power versus θ with 160- and 0-ps optical trigger delay, respectively, between adjacent antenna elements. Note UWB beam steering.

oped for applications such as impulse radar, ranging, and impulse communications.

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