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<p>A novel optically excited, frequency invariant, coplanar stripline antenna that we developed is presented. A comprehensive full wave analysis of optically excited coplanar striplines developed by us is also briefly reviewed. The work confirms the earlier hypothesis regarding the existence of new mechanisms. The reported findings imply the existence of a deeper and more fundamental physics underlying the optical generation, sensing and control of "electromagnetic radiation." An extensive bibliography is provided. As of August 1991 the following characteristics have been achieved: [Center frequency - N/A* Bandwidth &gt; 1THz (3 dB received power); Beam quality &gt; 99% TE<sub>00</sub> Gaussian; SNR &gt; 10<sup>5</sup>, Energy output 25 femtojoules per pulse; Energy efficiency 0.003% (optical to electromagnetic)]</p> <p>*The concept of center frequency is not applicable as the frequency response of the system is flat in between the frequency limits imposed by the smallest and largest</p>			
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Dear Dr. Schlossberg,

In 1984 we initiated work on AFOSR grants (Optical Generation, Control and Sensing of Millimeter Waves - No.AFOSR-88-0106). Let us briefly review the scientific salients.

In 1984, in my proposal to you I advanced the hypothesis of the existence of entirely new mechanisms that would extend the bandwidth of optically generated radiation to the femtosecond / terahertz regime. My primary objective was to discover and understand qualitatively new effects to provide a scientific basis for the development of high speed integrated optoelectronic device technology. I proposed to achieve this objective by studying certain model systems. Our work was based upon my earlier work at NRL [DEFONZO, 1979], [Pat.# 4282499;4263570, 1981], work at AT&T Bell Labs Murray Hill [AUSTON, 1975] and work at AT&T Bell Labs Holmdel [DOWNEY, 1983]. Our work during the period of the grants was complemented by work at IBM Thomas J. Watson Labs [GRISCHKOWSKY, 1987 a&b; ARJAVALINGAM, 1990 a,b&c]. This line of research was continued at AT&T Bell Labs Murray Hills and Columbia University [ZHANG, 1990 a&b]. The work continues at these institutions and has evidently expanded to other institutions. We need not elaborate incidental work here. It is useful to briefly review the work complementary to ours in greater detail.

In 1975, Auston studied the generation and control of transient pulses by photoconductive switching of microstrip structures on semiconductor substrates[AUSTON, 1975]. He shorted gaps in biased striplines photoconductively with picosecond optical pulses and studied the duration of the electrical pulses that propagated on the stripline. Much of the effort throughout the decade was concentrated on reducing electrical pulse duration. By 1978 it was becoming increasingly clear that shortening the pulses below ten picoseconds was difficult in these structures [DEFONZO, 1978]. In 1983 Downey [DOWNEY, 1983] reduced the duration of the pulse to slightly below five picoseconds and found that the limiting mechanism to shorter pulses in the Auston switch was due to electromagnetic radiation into the substrate. Downey's results inspired Auston to study this radiative mechanism into the substrate [AUSTON, 1984]. Meanwhile, in 1979 DeFonzo had eliminated the microstrip and any other electrode structures and was generating and controlling electromagnetic radiation by optically injecting electrons/holes into bare semiconductors. As of 1984 the following hypothesis had been advanced by me as documented in my proposal to AFOSR: *There exist qualitatively new mechanisms that extend the bandwidth of optically generated coherent electromagnetic pulses from the (then) limiting bandwidth of 50 GHz to bandwidths greater than 1 THz.*

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effect [HU, 1990]. Auston removed the metal dipole and biasing structures from the radiator and studied the rectified radiation off the surface of the semiconductor substrate directly pumped by femtosecond optical pulses. Among the more important characteristics of Auston's fixed frame dipole system are:

- Optical steerability
- Energy scaling

Varying the angle of incidence of the input optical beam corresponds to varying the phasing of the fixed frame dipoles on the surface of the substrate which leads to a change in the direction of output radiation. This mechanism enables the optical steering of the electromagnetic beam by varying the angle of incidence of the optical beam. The absence of the electromagnetic impedance matching structures in Auston's fixed frame dipole radiator should improve the energy efficiency (optical to electromagnetic). The presence of electrical bias electrodes enables energy scaling through the application of electrical bias to the substrate surface. The beam quality is implicated in considerations of useful output energy and useful optical steerability. Low beam quality reduces ultimate utilizable energy density. Effects of optical steerability and electrode free radiation is indicated by the deviation of the output beam quality from that of a  $TEM_{00}$  mode of free space. Auston discovered two new effects -- optical steerability and bias free semiconductor surface radiation. As of the end of our grant period Auston had achieved the following characteristics: {Center frequency- 0.5THz; Bandwidth -0.3 - 0.6 THz (3 dB received power); Beam quality - ?, SNR- ?, Energy output - 300 femtojoules per pulse; Energy efficiency - 0.4% (optical to electromagnetic)}\*

At the end of the grant period, people were routinely generating electromagnetic radiation optically with 3 dB bandwidths in the range of 0.3 - 0.8 THz and using this radiation over the entire bandwidth from 20 GHz to 2 THz [GRISCHKOWSKY, 1990 a&b; ARJAVALINGAM, 1990a; AUSTON, 1985] to perform precise spectroscopic studies of materials. These studies were based upon the "fixed frame" dipole radiators just discussed and "moving frame" dipole radiators that we are about to discuss. These two novel radiators can be classified according to whether the dipoles generated involve virtual [KLEINMAN, 1984] electronic transitions, or as we report here involve real electronic transitions. One can reasonably conclude from the foregoing that the hypothesis I advanced in my initial proposal was thoroughly tested and validated by the end of the grant period.

A new hypothesis has recently emerged as a result: *Coherent electromagnetic modes of space can be created by the successive symmetry breaking annihilations of existing coherent modes of space.* Three important implications of this hypothesis are:

\*The numbers for the output energy and energy efficiency have been calculated from the most generous interpretation of the figures provided in the authors paper [Zhang, 1992]. The characteristics provided in these papers are very obscure relative to those that can be obtained from Grischkowsky and we caution the reader to prudence.

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- We could formulate a qualitatively new scientific framework with a fundamentally new model of electromagnetic radiation.
- The scientific framework would provide a means of determining the ultimate limits of beam quality , power scaling effects etc., by simulation in advance of expensive experiments.
- The framework would offer insights into possible work-arounds to trade-offs in the systems described above.

Three unique results required to infer this hypothesis are;

1. The theory of the crucial role of symmetry in radiation effects[ PHATAK & DEFONZO, 1990b].
2. The first comprehensive full wave analysis of the radiation and propagation properties of "moving frame" dipoles [PHATAK&DEFONZO, 1990a]. The full wave analysis is a complete, in a classical sense, electromagnetic theory of modes.
3. The discovery of an archetype[ DEFONZO, 1987] [DEFONZO, Pat. # 4855749] which embodied the theory and enabled operationalization of the mathematical theory.

Let us suppose for the moment our new hypothesis was inferable without these results. The hypothesis directly implies the necessity of a theory that subsumes classical electromagnetics. The hypothesis could not be brittle if we did not exhaust the full predictive capabilities of classical electromagnetic theory. Models such as "Cerenkov" radiation from moving dipoles are subsumed by full wave analysis and hence cannot exhaust the predictive capabilities of classical electromagnetics. Thus in order to make the hypothesis brittle we need a comprehensive full wave analysis. This contradicts our supposition involving the second result. Similar arguments could be made for the suppositions regarding the remaining two results. In this way one can clearly, concisely and concretely convince oneself of the necessity of our results and our logically subsequent hypothesis. Let us now turn our attention to the discovery, development and uses of our particular radiator system.

When an optical pulse generates electron-hole pairs in the photoconducting gap between the biased microstriplines in our antenna they begin to polarize in the bias field and under ideal conditions a traveling wave is launched along the coplanar striplines by the photo-induced current. If the coplanar stripline were ideal (no material or substrate losses) the traveling wave propagates along the stripline with no losses because the stripline is a TEM structure. To an observer in the rest frame of the traveling pulse moving at the velocity of light away from the generation point along the propagation axis of the stripline the photo-induced current on the stripline appears to be a space charge dipole. This is the dipole appearing as the "moving frame" dipole to an observer in the rest frame. As the propagating dipole encounters the exponential flare a series of annihilation events occur. Let us briefly examine one of these events. Each event can be viewed as the annihilation of a dipole quanta and results in the release of the

photons comprising the TEM field "contained" by the moving frame dipole. The microscopics and mesoscopics of the annihilation process are not yet fully understood. It is clear from symmetry arguments that the sequence resulting from the series of annihilations is an exponential function along the direction of propagation [DEFONZO unpublished]<sup>#</sup>. The scaling symmetry uniquely specifies the form of the electrode pattern needed to maintain the phase, polarization, amplitude and frequency relationships of the guided TEM modes covariant under transformations into free space. In the absence of other asymmetries on the flare structure the output radiation coherently replicates the packet fed to the antenna. The termination of the flare structure is an inescapable asymmetry which introduces a low frequency cut-off for this replication process.

Practically speaking, the coplanar striplines had a substrate entailing additional asymmetries. The presence of a substrate leads to electromagnetic radiation as the pulse propagates along the striplines. Previous attempts of full wave analysis [HASNAIN, 1986] of these striplines could not account for the radiation satisfactorily due to difficulties originating from the poles encountered in the Greens function. We dealt with these poles in a comprehensive full wave analysis of the radiation and propagation properties of pulses along such structures [PHATAK, 1990a&b]. We demonstrated for the first time that finite thickness substrates result in poles in the Green's function that correspond to the modes of the finite substrate. Infinite substrates correspond to branch cuts in the Greens function. Our theoretical contribution provides an adequate and sound basis for the analysis of mechanisms leading up to replication.

Our radiation systems have been characterized in detail [PASTOL, 1988 ; LUTZ, 1989]. The system has the following typical characteristics {Center frequency- N/A \* Bandwidth >1THz\*\* (3 dB received power); Beam quality > 99% TEM<sub>00</sub> Gaussian; SNR > 10<sup>5</sup>, Energy output 25 femtojoules per pulse; Energy efficiency\*\* 0.003% (optical to electromagnetic)}. The observed bandwidth of 25GHZ to 100 GHZ represents the empirical lower bound of the bandwidth of the system. The true bandwidth of the system is determined by the smallest and largest dimensions of the exponential flare. The energy efficiency here includes the efficiency of coupling the energy from the optical pulse into the photocurrent in the substrate. This coupling efficiency is of comparable magnitude in all the systems described here. However in our system the efficiency of coupling energy from the current generated into the modes of free space is nearly 100% which is not the case with any of the other systems. Our radiation systems are uniquely and fully frequency invariant in amplitude, phase and polarization. Earlier frequency invariant structures such as the equiangular spiral and the Vivaldi structure are known to be only partially

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<sup>#</sup> DeFonzo has shown that exponential structures scale in space and time.

<sup>\*</sup> The concept of a center bandwidth is not entirely applicable due to the frequency invariant nature of these antennas.

<sup>\*\*</sup> This is the theoretical bandwidth determined by the minimum and maximum dimensions of the antenna.

invariant. The radiation system we developed has been used extensively at IBM Thomas J. Watson Labs for spectroscopic studies of a variety of materials [ARJAVALINGAM, 1990a; PASTOL 1989 ab&c; ] including anisotropic materials [ARJAVALINGAM, 1990b&c]. While we have not kept track, we know that our radiation system is being used in other research organizations. These applications validate the near ideal properties of our optoelectronic radiation system that are of practical and fundamental importance.

In 1984, I advanced a hypothesis that had far-reaching consequences in the advancement of the field of optical generation and control of microwave radiation. The work that followed was primarily inspired by the pioneering efforts of Auston [AUSTON, 1975] and myself [DEFONZO, 1979],[Pat.# 4282499;4263570. 1981]. Interestingly, Auston developed free space radiating structures based on direct optical pumping while we developed free space radiating structures based on striplines. This was a reversal of our earlier roles. As we have seen, this crossing over and co-inspiration has led to a great deal of experimental and theoretical work being performed, much of which was funded by AFOSR. The work performed so far represents a significant advance in the area of optical generation, control, and sensing of "electromagnetic radiation." Also, we have advanced a new hypothesis that we expect to be of momentous impact in future work in the area. From the foregoing one can reasonably anticipate the continuing evolution of research and development in what we have found to be an interesting and exciting field.

The success of our work in the area is evidence of the effective funding approach used by AFOSR in this instance. The preparation of this report would not have been possible without graduate students, Anand Raman, Thomas Kuchta and Serguei Sokolov.

Cordially yours,

A handwritten signature in cursive script, reading "Alfred P. DeFonzo". The signature is fluid and stylized, with the first letters of the first and last names being prominent.

(Alfred P. DeFonzo P.I.)

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