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CONFIGURABLE CONFORMAL IMPULSE RECEIVE ANTENNA

G. Hawkins Kirk

Scientific Applications & Research Associates (SARA), Inc.
6300 Gateway Drive
Cypress, CA 90630-4844

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Final Report

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AIR FORCE RESEARCH LABORATORY
Directed Energy Directorate
3550 Aberdeen Ave SE
AIR FORCE MATERIEL COMMAND
KIRTLAND AIR FORCE BASE, NM 87117-5776

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This report has been approved for publication.

//SIGNED//
JOSEPH L. BROECKERT, 2d Lt, USAF
Project Manager

//SIGNED//
REBECCA N. SEEGER, Colonel, USAF
Chief, High Power Microwave Division

//SIGNED//
L. BRUCE SIMPSON, SES
Director, Directed Energy Directorate

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14. ABSTRACT
Among leading-edge research concerns in ultra-wideband (UWB) radiofrequency (RF) methods, it has recently become important to devise antennas to satisfy the following conditions as much as possible: (a) be UWB responsive; (b) be preserving of impulse waveform structure; (c) be coplanar (thin) and surface conformal; and especially (d) be operable on *conductive* support (e.g. metal-skin of aircraft). Conditions (a+d) are *almost* mutually exclusive among prior-known designs, and combinations (a+b+c) have been implemented only recently. We satisfied condition (d) from the start by deriving from a microstrip "patch" antenna basis. Then, revisiting conventional theory on frequency independent antennas, we added considerations of distributed feedwork and textured impedances related to "electronic band -gap" (EBG) structures. The resulting solution space is broad and allows for much further refinement. During optimization analyses, we achieved proof-of-concept in a study model named CATSPAW - for "Configurable-Aperture Tunable-Substrate Patch-Antenna for Wideband" – with steerability and channelized sub-spectral capabilities for advanced radar methods.

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CONFIGURABLE CONFORMAL IMPULSE RECEIVE ANTENNA

1. Introduction

This Final Report describes work performed under a Phase I SBIR program (SBIR AF04-006) that began in May 2004 for the overall objective of developing "co-planar conformal impulse receive antenna arrays that can be integrated into airborne platforms such as Unmanned Aerial Vehicles (UAVs) and aircraft". The Phase I goal was to demonstrate feasibility experimentally with a small scale antenna design. This report summarizes the considerations that provide the shortest path to reconstructing our findings. The technical level of our discussion is aimed for readers with basic familiarity in microwave theory and antenna design as given in the popular texts by Pozar, Balanis, Stutzman and Thiel.

1.1. Level of Difficulty

The in-going difficulty of this program's objective is suggested not only by a lack of prior-known solutions but also in what is almost a practical (not theoretical) contradiction for the combination of the implied characteristics: (a) Ultra Wideband (UWB) response; (b) preservation of impulse waveform structure; (c) coplanar (thin) and surface conformal; and, especially (d) operability on *conductive* support (e.g. metal-skin of aircraft). Conditions (a+d) have been *almost* mutually exclusive among prior-known designs, and combinations (a+b+c) have been implemented only recently.

1.2. Special Considerations – Emphasis on Signal Waveform Integrity

There are crucial differences among design considerations for the cases of narrowband vs. ultra-wideband and the special "impulse" array contexts. Between an antenna and its processing amplifier electronics, variation of impedance characteristics along the signal path determines the extent by which a signal waveform is reverberated and thereby contaminated by a blurry superposition of echoing self-copies. Strong discontinuities or gradients of impedance (relative to principal wavelengths) produce substantial reflections of incident signals. In narrowband operation, considerable freedom exists for designs to compensate for variation of signal-path impedances and retain minimum levels of signal degradation. Yet with wideband operations, the frequency dependence of impedance relations prevents the majority of narrowband compensation techniques from being applicable.

In array designs, mutual coupling interactions can significantly complicate impedance relations. In narrowband applications, mutual coupling relations are analyzable in terms of frequency domain phasor impedances of the usual "Z = R + jX" form. However, it is well known that mutual coupling relations become nontrivial relative to steering and wavefront angle of arrival. For multi-frequency applications, even though they may not be wideband, it happens that mutual coupling relations are waveform dependent in *detail*, including history, and so the implications for impedance considerations quickly become highly complex and nontrivial.

Beyond dealing with impedance-dependent reverberation effects, the preservation of waveform integrity also requires accounting for potential phase distortion. The majority of wideband antenna systems suffer from frequency-dependent non-uniform velocities of wave propagation – with effects referred to as "dispersion". There also tends to be a fair degree of dependence of harmonic phase relative to angle-of-incidence of the wavefronts relative to the antenna structure – with effects referred to as "aberration". While mutual coupling effects increase with compactness of antenna design, yet smallness of "electrical size" (relative to principal wavelengths) is an advantage for minimizing phase differences across the antenna structure. Though a "tiny" antenna may be weak in sensitivity, yet it is relatively easy to make it non-dispersive. But if the antenna is larger than a fair fraction of any brief pulse-width of interest, then phase relations across the antenna-width become too large for compensation or waveform preservation.

So we are faced with the prospects of designing an antenna that is large enough for sensitivity purposes yet small enough for practical waveform preserving techniques. UWB per se is not sufficient – phase relations must also be preserved.

Finally, at the level of array design, steering is achieved in terms of signal summation and constituent sub-signal coherence. In narrowband radar, the steering of an array's radiation pattern can be simply achieved by applying phase-shifts to the signal chain in the transmission feedwork. But in UWB and impulse radar, phase-shift methods alone are insufficient. Just as happens white light shining through a prism, which spreads the visible wavelengths into the colors of a rainbow (around an octave in frequency range), the same separation happens for UWB microwaves interacting with a phased array. To steer for UWB signals, one must apply true-time-delay signal methods [1]-[4].

2. Preparatory Phase

Following a program start-up meeting with AFRL/DEHP personnel at Kirtland AFB in mid-May 2004, we revisited the literature to confirm the apparent fastest path(s) to the program goals. With the given combination of design factors, we determined that it seemed best to proceed in the following mixed parallel-series order of intermediate design steps, by:

- beginning with operability on conductive substrate (to satisfy applicability upon a typical aircraft surface);
- co-beginning with “widebanding” methods to yield ultra-wide bandwidth (covering the frequency range of 200MHz-2GHz); and *then*
- establishing phase linearity for waveform preserving impulse responsiveness.

Accordingly, the intermediate stages of our progress evolved via:

- a beginning in “microstrip patch antenna” designs (which work on conductive substrate);
- a co-beginning in considerations of multi-resonant stagger-tuning (for achieving wide bandwidth);
- and then finally to surface-wave guidance methods (to control phase centering and uniformity), combined with experimental reconfigurable tuning capabilities.

Our reasons for deciding upon this parallel-series sequence were:

1. the efforts seem comparable between modifying a conductively-backed patch antenna to achieve wideband response versus modifying a wideband antenna into operating with a conductive backing;
2. it seems to be somewhat easier (within our understanding) to adjust a wideband antenna toward phase linearity than it is to maintain phase-linearity in an antenna while modifying toward wideband response.

3. Design Trade Studies

Conventional theory on wideband and/or so-called "frequency independent" designs fails to supply us with more than a bare minimum of options under the constraint conditions of (1) "co-planar" (thin), (2) "conformal" (to fit closely with underlying support surface), and (3) operability upon a conductive surface (such as a typical aircraft wing or fuselage). The first two constraints reduce consideration to "flat" antennas, among which the widest bandwidths are achieved by log-periodic dipole arrays (LPDAs) and flat spiral designs. The third constraint is severe (implying partial cancellation of the electromagnetic fields), with the result that the range of applicable designs is thereby limited to variations from the family of so-called "microstrip patch" or "surface-wire" antennas - which inherently contain an underlying conductive surface or groundplane.

Though recent literature has advertised the development of "broadband" microstrip patch antenna designs [5]-[6], yet relatively little of the published analyses appear to devote attention to the *fundamental factors* that can be harvested for ultra-broadband response. One of the best summaries is by Pozar and Schaubert; Microstrip Antennas [7], pgs 155-166). Basic modifications that use shorting posts, capacitive stubs, and/or stacking arrangements have culminated in a modest bandwidth of up to ~70%. Again, the largest bandwidths appear to have been achieved by stagger-tuned arrangements related to Yagi-Uda and log-periodic dipole arrays (LPDAs) reaching a 2-octave bandwidth for a VSWR of 2.3. We were encouraged by finding that the published analyses supported our independent notions for improving bandwidth by departing from LPDA structure [8]-[14].

3.1. Lessons from Published Literature

Figures 1-3 below illustrate the context of our considerations. First, we see a basic representation of a microstrip antenna. The radiation coupling mechanism occurs through a combination of (a) induction of surface currents whose flow is governed by the surface conduction pattern, and (b) charge densities that collect near the edges of the surface conduction pattern, which produce fringing fields that couple with the underlying ground-plane conductor. The resulting charge and current densities modulate in time as electromagnetic fields propagate across the patch. Large amplitudes of excitation occur when the frequency content of applied fields matches with resonances of the patch natural oscillation. [7], [15], [16].

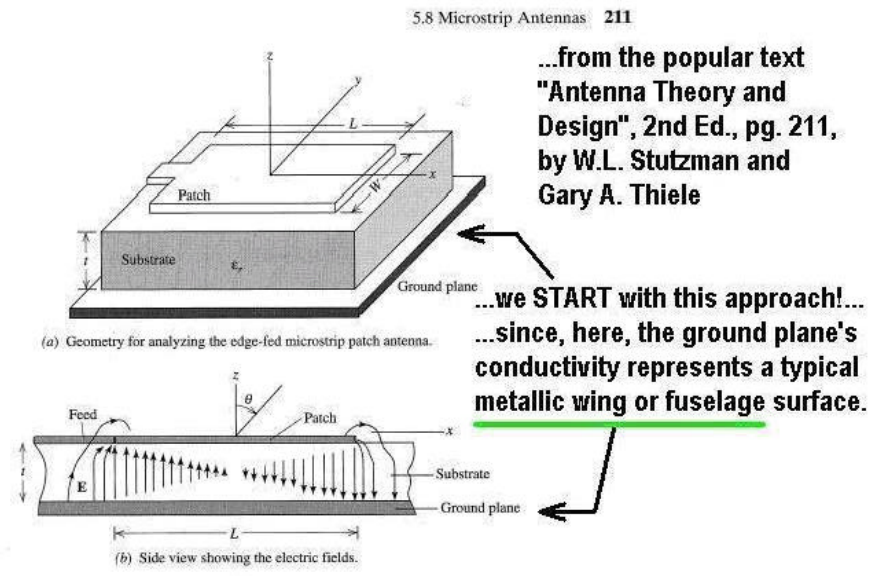
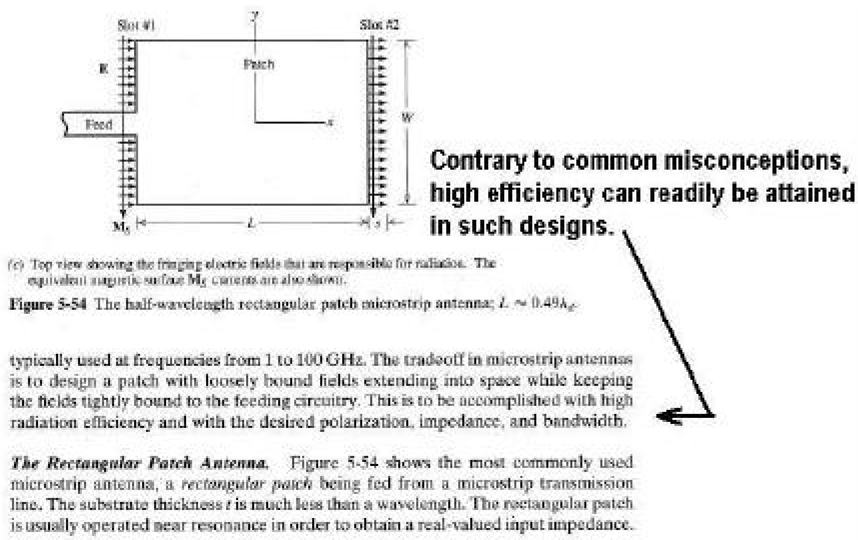


Figure 1 Basic microstrip patch architecture – inherent operability with underlying conductor surface [15].



(c) Top view showing the fringing electric fields that are responsible for radiation. The equivalent magnetic surface M_S currents are also shown.

Figure 5-54 The half-wavelength rectangular patch microstrip antenna; $L \approx 0.49\lambda_g$.

typically used at frequencies from 1 to 100 GHz. The tradeoff in microstrip antennas is to design a patch with loosely bound fields extending into space while keeping the fields tightly bound to the feeding circuitry. This is to be accomplished with high radiation efficiency and with the desired polarization, impedance, and bandwidth.

The Rectangular Patch Antenna. Figure 5-54 shows the most commonly used microstrip antenna, a *rectangular patch* being fed from a microstrip transmission line. The substrate thickness *t* is much less than a wavelength. The rectangular patch is usually operated near resonance in order to obtain a real-valued input impedance.

Figure 2 High efficiency is possible with microstrip patch design [15].

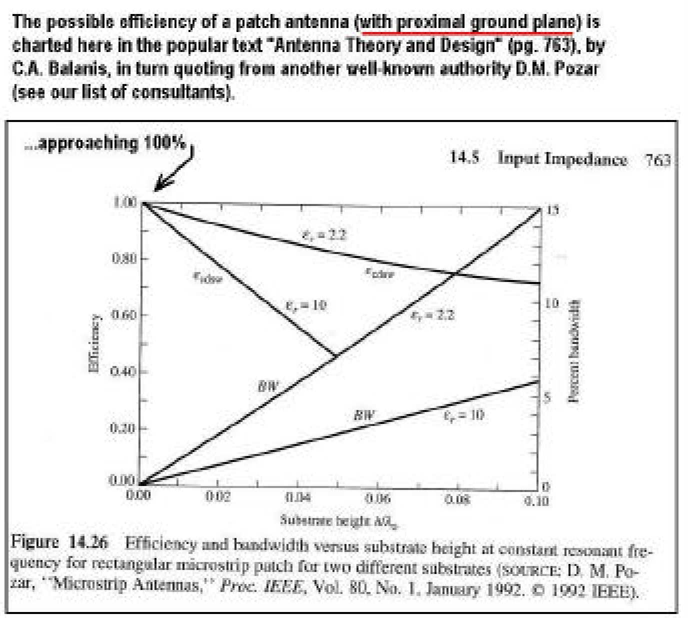


Figure 14.26 Efficiency and bandwidth versus substrate height at constant resonant frequency for rectangular microstrip patch for two different substrates (SOURCE: D. M. Pozar, "Microstrip Antennas," *Proc. IEEE*, Vol. 80, No. 1, January 1992. © 1992 IEEE).

Figure 3 Trade-offs between radiation efficiency and bandwidth [7], [16].

The literature is full of variations on the theme. Faced with such variety, we naturally wondered about the best place to begin. The potential variety is hinted-at in Figure 4.

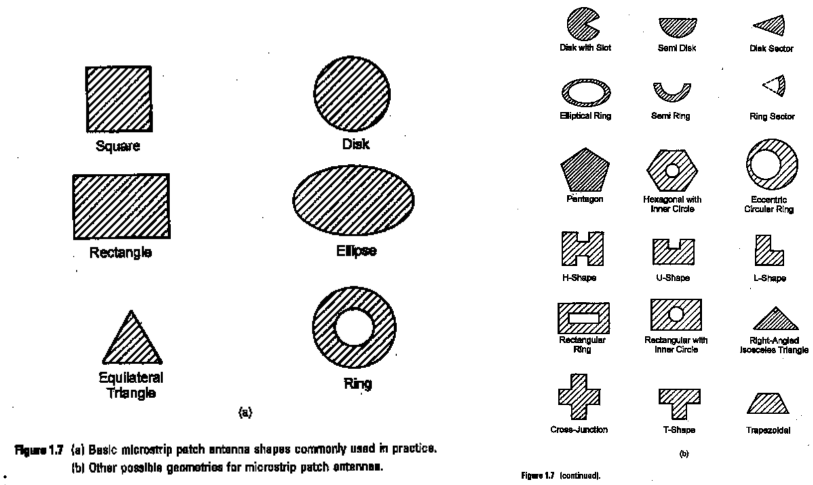


Figure 4 Dizzying variety of basic designs [6], [17].

We resolved our puzzlement by revisiting the best survey articles and then by identifying the <u>fundamental attributes that relate most directly to the issue of extending bandwidth</u>. Figures 5 and 6 depict the prevailing methods [12].

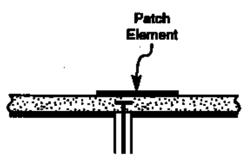


Fig. 3. Bandwidth improvement by tuning out probe inductance with a series capacitor in the feed probe.

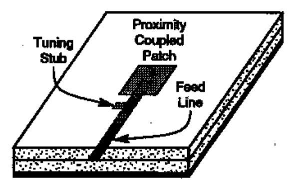


Fig. 4. Bandwidth improvement using a proximity-coupled patch in conjunction with a simple stub tuner.

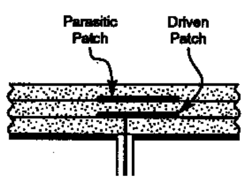


Fig. 5. Bandwidth improvement using dual resonances obtained with stacked patches.

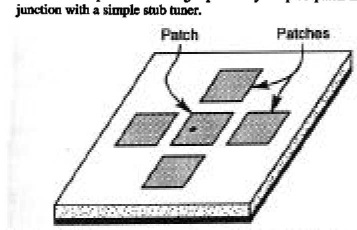


Fig. 6. Bandwidth improvement using multiple resonances obtained with edge-coupled parasitic patches.

Figure 5 Methodical approach to improving bandwidth [12].

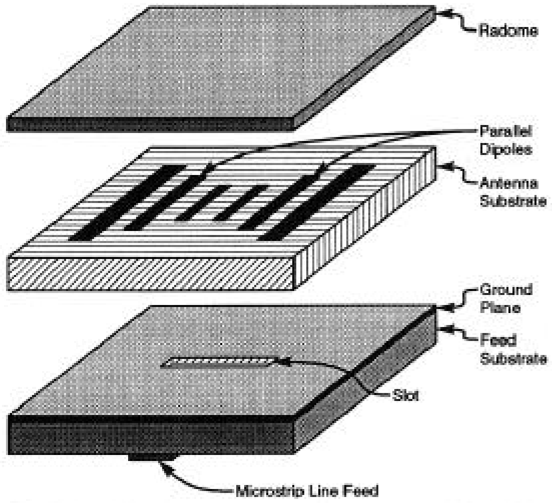


Fig. 7. Bandwidth improvement using multiple resonances obtained with aperture-coupled dipoles of variable size.

Figure 6 Stagger-tuning is a proven basis for general "widebanding" [12].

For the "frequency independent" theory side of our approach, we revisited the literature with a concentration around Log-periodic, Yagi-Uda, and related "herringbone" dipole arrays, and we also found the famed "Goubau" wideband low-Q design interesting. In order to solve for phase dispersion in the antenna, it is important for the design to be "electrically small". Consequently it is good to find that such dipole array antennas can be made significantly compact relative to their operating wavelengths. This is shown in Figure 7, which was on the cover of the December 1972 issue of the Microwave Letters journal, and discussed therein [11]. Observe: The extended conduction paths at the ends of the main dipoles help to compensate for reduction in the overall size. This lesson is repeated in the evolution of compact microstrip patch design.

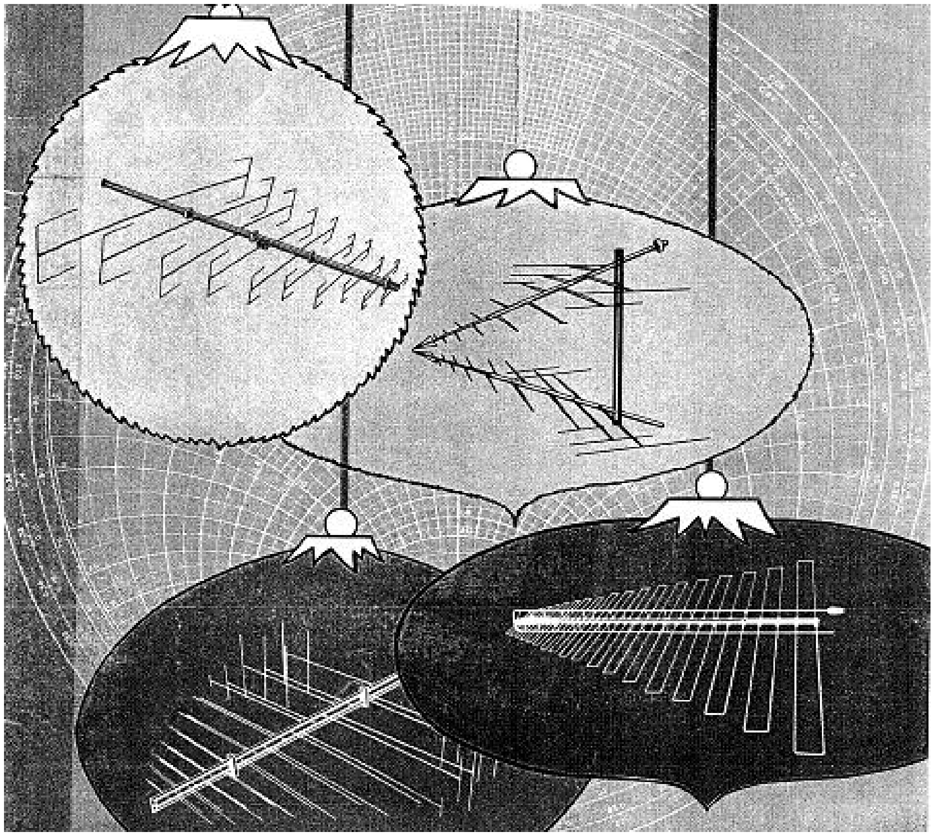


Figure 7 Lessons for reducing size of stagger-tuned arrays [11].

Figures 8 and 9 show some variations of “size-reduced” LPDA antennas. [11]

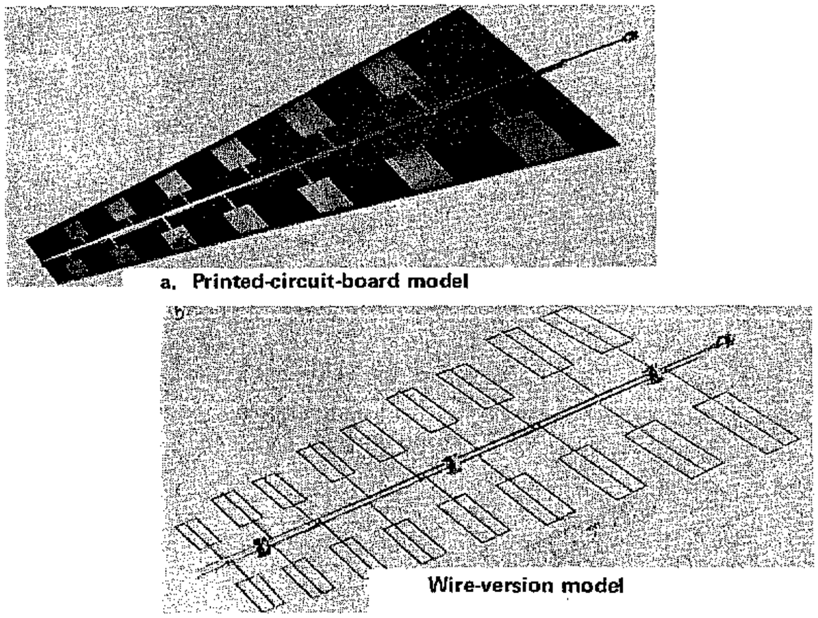


Figure 8 Size-reduced printed-area and surface-wire LPDA antennas [11].

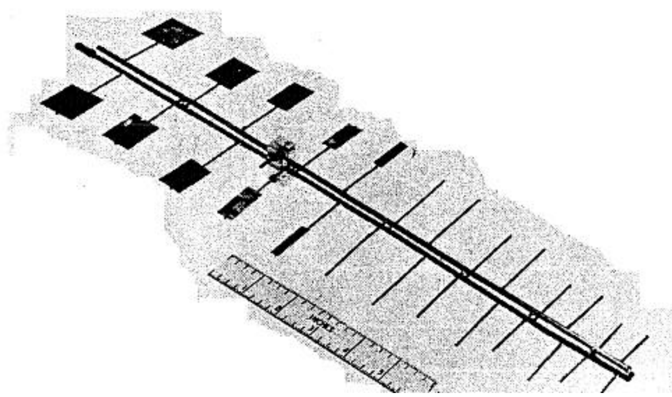


Figure 9 Size-reduced quasi-log-periodic and mixed dipole array antennas [11].

Next, Figure 10 depicts microstrip patch versions of LPDA and Yagi-Uda designs [8], [18]. Hall's paper also discusses departure from LPDA design.)

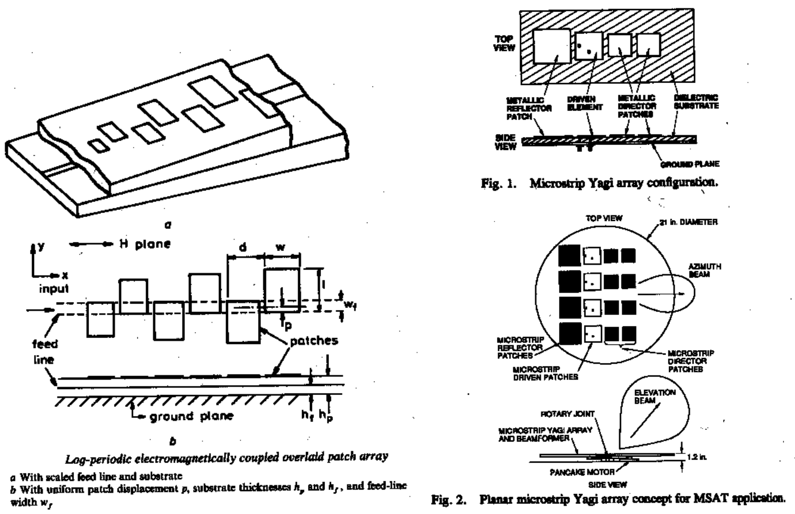


Figure 10 Microstrip patch versions of log-periodic dipole array & Yagi-Uda antennas [8], and [18].

Additionally, in the Microstrip Antenna Design Handbook by Bhartia et al [17], methods of widebanding that depend on current-path diverting geometry are also explored. A few examples are seen in Figures 11 and 12 below and following:

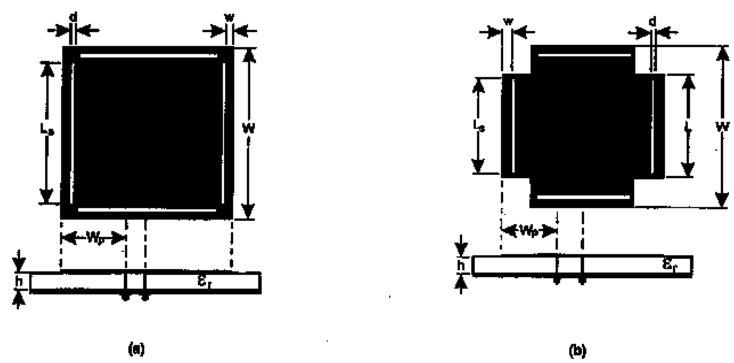


Figure 11 Top view of (a) slotted square and (b) slotted cross-patch antennas for dual-

polarization operation. Current-path diverting geometry helps to improve bandwidth [17].

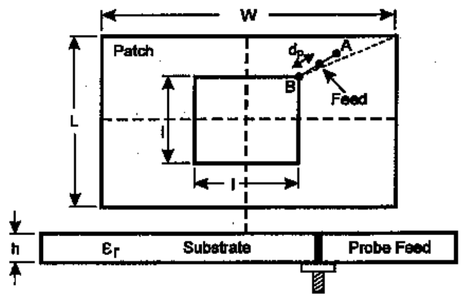


Figure 12 Top view of a rectangular ring microstrip antenna. The ring is excited along the diagonal for dual-frequency operation [17].

By repeated nesting of the current diverting slots, holes, etc., we can dramatically reduce the primary resonant frequency of oscillation and achieve a long-wave resonant antenna within a small *compact package*. <u>Lesson</u>: The diverted current paths extend the cycling time. Figure 13 below shows a nested folded dipole [17].

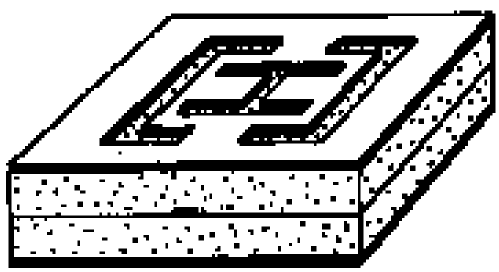


Figure 13 Nested folded dipole – shows repetition of the theme of current path contouring [17].

3.2. Conceptual Convergence… Patches Within Patches!

In the convergence between our parallel approach beginnings, we realized an intermix of surface-wire and patch designs such that further refinements to the surface-wire structure consisted of patchwork while further refinements to the patch designs consisted of wirework.

The lesson here is: the elements of a dipole array, perhaps formed as current-contouring branched and cross-laid wirings, may themselves be regarded as patch structures that in-turn may be dipole arrays, and-so-on by iterative nesting (but NOT fractal).

3.3. Selected Design Bases to build upon

Accordingly, one of our parallel starting points for approaching UWB response was chosen to be a "Logi" design (manufactured by Kent Brittain; Ham radio call sign WA5VJB – see [19]), which is represented as a deviation from LPDA form that adapts from Yagi-Uda array design to typically achieve a 6db gain and span ~ 1.5 to 2 octaves in bandwidth. Note however that the "Logi" antenna is not a patch antenna designed to operate in proximity with a groundplane, so there are nontrivial considerations required for adapting into patch form. A significant amount of rescaling and additional stagger-tuning modifications are needed to extend the ~ 1.5 to 2 octave response to our 10:1 frequency range goal (200 MHz - 2 GHz). (See Figure 14.)

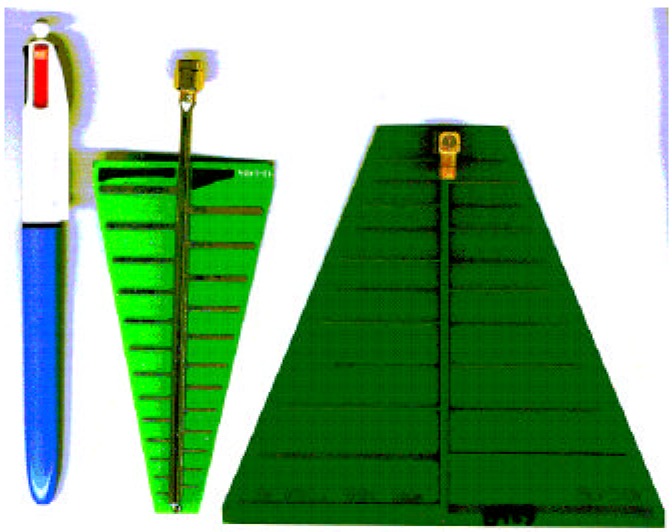


Figure 14 Comparison between a "compact size-reduced LPDA" vs. a "Logi" antenna design. (A writing pen is shown for scale, at left. At middle: an LPDA with frequency range of 1.6 to 6.4 GHz. At right: a "Logi" antenna for 900 MHz to 2.6 GHz.) [19]

Our other parallel starting point began with a microstrip patch outline and evolved through a series of exercises in sculpting diverted currents into stagger-tuned patterns with stacking arrangements between the conductive and dielectric layers. In early stages, this yielded some designs reminiscent of a Goubau antenna; however, in patch form. As seen in Figures 15-17, it did not take long to conclude that nested-slotted structures in overlay also provided a good motif for correlating from aspects in the structure to features of interest in the spectral response [17].

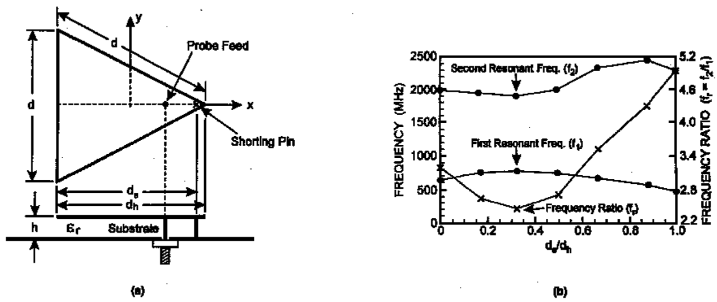
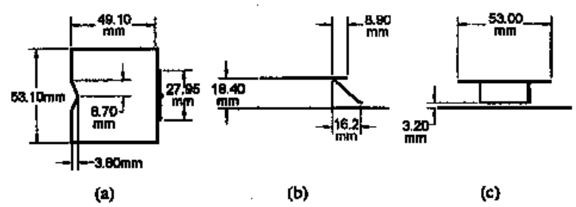
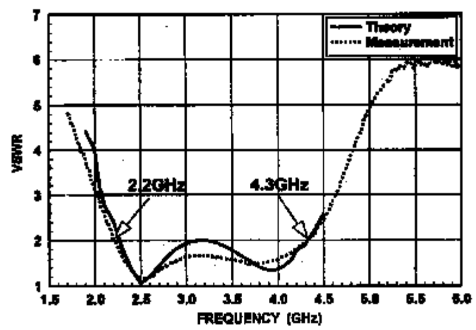


Figure 15 (a) geometry of a dual-frequency triangular microstrip antenna with a shorting pin. (b) variations of the resonance frequency ratio versus position of shorting pin. Design measurements: d=50mm, h=0.762 mm, e_r=4.4. [17]



Various dimensions of the antenna shown in Figure 9.39(a). (From [63]. © 1998 IEEE. Reprinted with permission.)



Comparison of measured and computed VSWR of the antenna shown in Figure 9.39(a). The dimensions of the antenna are given in Figure 9.40. (From [63]. © 1998 IEEE. Reprinted with permission.)

Figure 16 Comparison of measured and computed VSWR of a fin-shorted patch antenna. See [17]

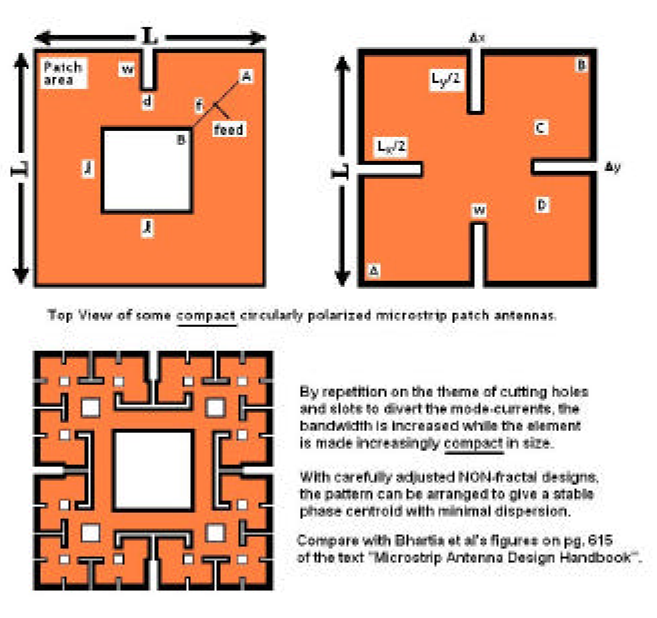


Figure 17 Frequency and polarization control is achieved by judicious arrangement of holes and slots and cuts.

LESSON:

Anisotropic conduction is a key property for modifying resonant structure interactions. While charge distributions may appear similar among the design variations, yet the current paths through which those charge distributions are formed may be highly varied so as to significantly alter the timings of oscillation, polarizations, and respective patterns of coupling across the structure. The following references describe the modern basis for implementing these concepts:

1. "Focusing electromagnetic waves into an anisotropic conducting half-space", by: J. R. Wait, et.al, 1992, J.Phys.D: appl. Phys. Vol. 25, pp 1395-1399.

2. "The effect of conducting particle distribution on the behaviour of anisotropic conducting adhesives", D.J. Williams, and D.C. Whalley, Journal of Electronics Manufacture, Vol. III, No. 2, 1993, pp 84-95.

3. "Current-Carrying Capacity of Anisotropic-Conductive Film Joints for the Flip Chip on

Flex Applications", S.H. Fan, and Y.C. Chan, Journal of Electronic Materials, Vol. 32, No.2, 2003, p 101…

Phase I Innovative Approach

Following the investigation outlined in the previous section, the chiefly innovative portion of our work proceeded toward the issues of phase linearity and waveform preserving impulse response. For this, we considered how to adapt from microstrip-related filter [20]-[23] and coupling structures [24]. So-called "electronic band gap" structures, which are receiving increasing attention in recent microwave literature, express a variation on this theme (see Figures 18, [17]).

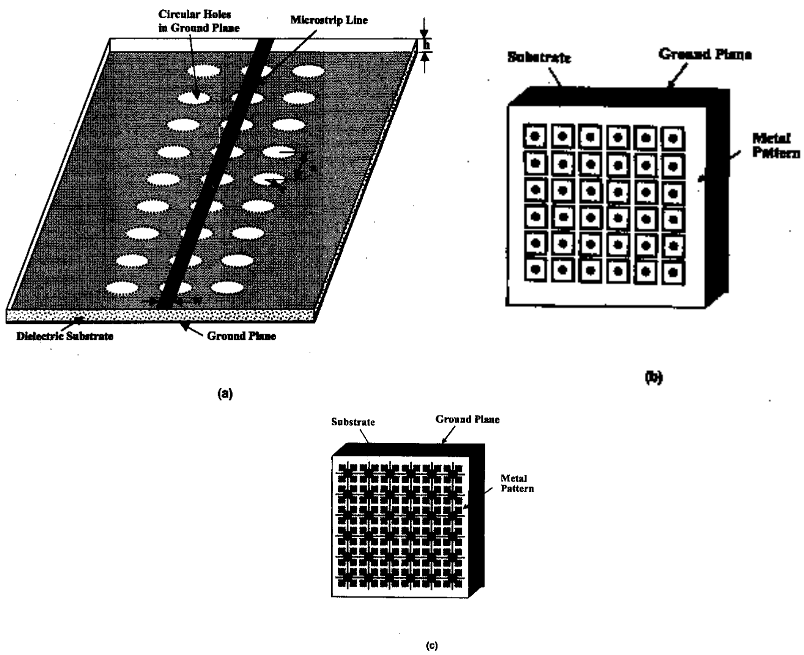


Figure 18 Three types of periodic loading of grounded substrate to obtain photonic bandgap characteristic: (a) Square lattice of etched circles in the ground plane; (b) Square lattice of small metal pads with grounding in the center; (c) Uniplanar compact PBG substrate. [17]

Finally, to resolve the implied complexity, we accelerated our experimentation to include a mixture of electronic and optical tuning and reconfiguration methods; which, AFRL's Dr. Carl Baum referred to in our interim meeting as being a "hardware Newton-Raphson method" (see Figure 19) [12], [17], and [6].

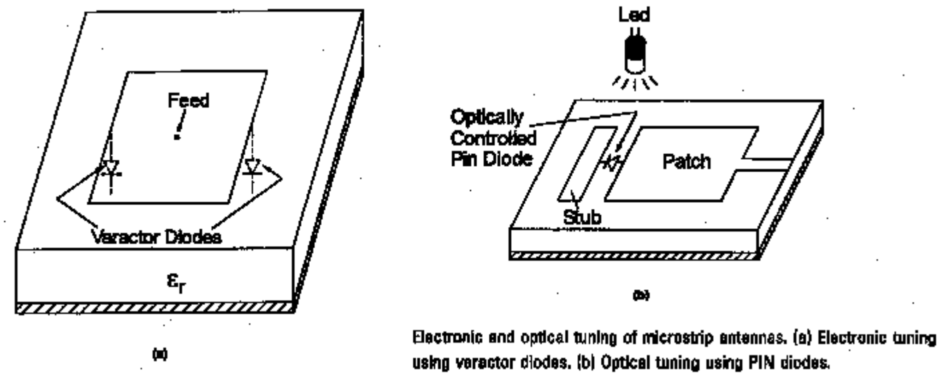


Figure 19 Electronic & photonic reconfiguration methods are described as experimental techniques in the literature going back over the past two decades ([6], [12], and [17]).

Aside from using electrically controlled varactors and optically controlled photodiodes, we have experimented with photoconductive, photovoltaic, and photoreactive materials placed between printed layers of textured impedance structures. These methods allow us to study alternative ways of coupling and tuning the structures of the antenna while minimizing spurious effects that normally occur with direct contact or proximity probes. Figure 20 shows two textured impedance structures suitable for optical control modifications.

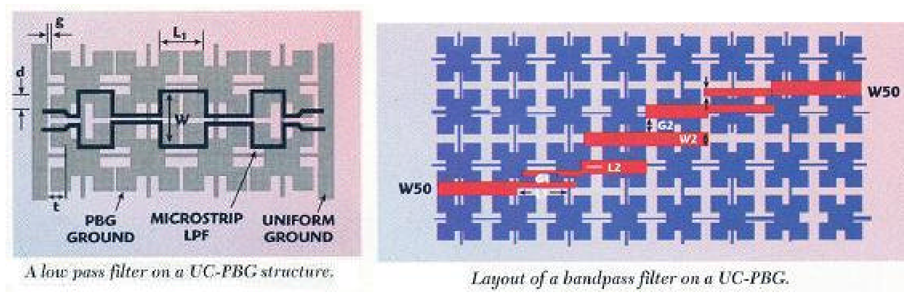


Figure 20 Example of periodic band-gap (PBG) textured impedance surfaces used to impose waveform filters and guidance channels: Our reconfigurable distributed impedance method allows for such RF sub-systems to be programmatically synthesized, induced, and adjusted in real-time according to adaptive operating requirements. [25]

3.4. Construction and Accelerated Design Refinement Process

The basic idea is to try to "stagger-tune" a complex array of interacting dipole structures by applying various reactive loadings and couplings among them. To understand this, it is best to start with a simple pair of dipoles tuned to nearby resonance frequencies, and then see how the bandwidth changes in response to the modifications. The overall goal is to both broaden and smooth the range of spectral response, as far and as deep as possible. However, the prevailing physical mechanisms in the system involve a trade-off between depth of response (sensitivity) versus bandwidth. (see Figures 21 and 22 below).

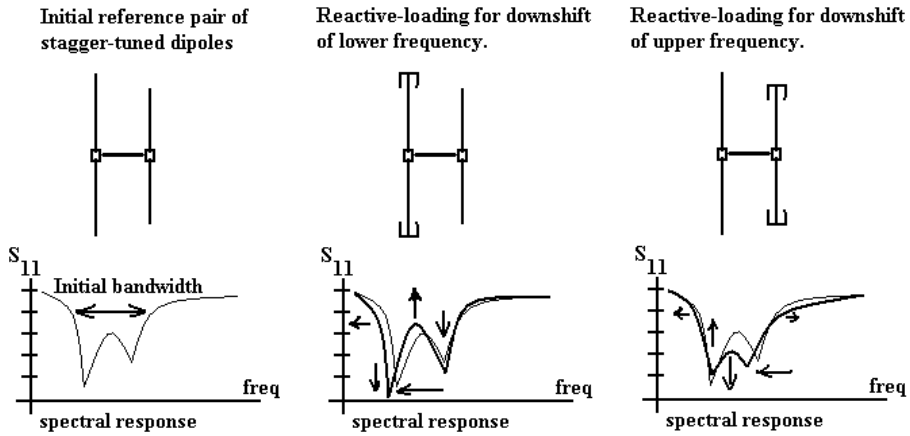


Figure 21 Effects of Stagger-Tuning modifications to BOTH broaden and smooth the response range.

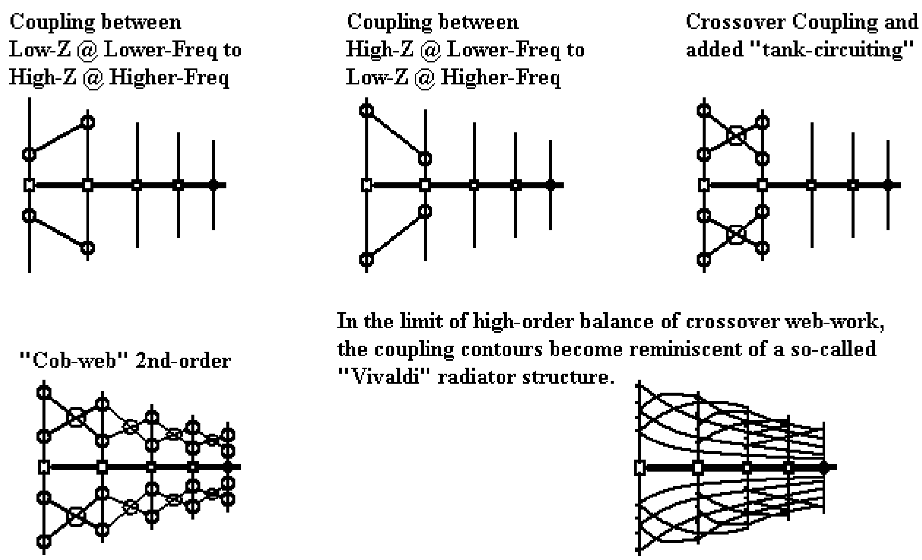


Figure 22 Progressive alterations to approach a smoothed resonance pattern by applying

weakly-coupled crossover networks and “rounding” of the impedance distribution.

To see if we could accelerate our design studies, we began testing modifications to a well-characterized LPDA antenna. We began with an examination of the distributed impedance characteristics. (See Figure 23.)

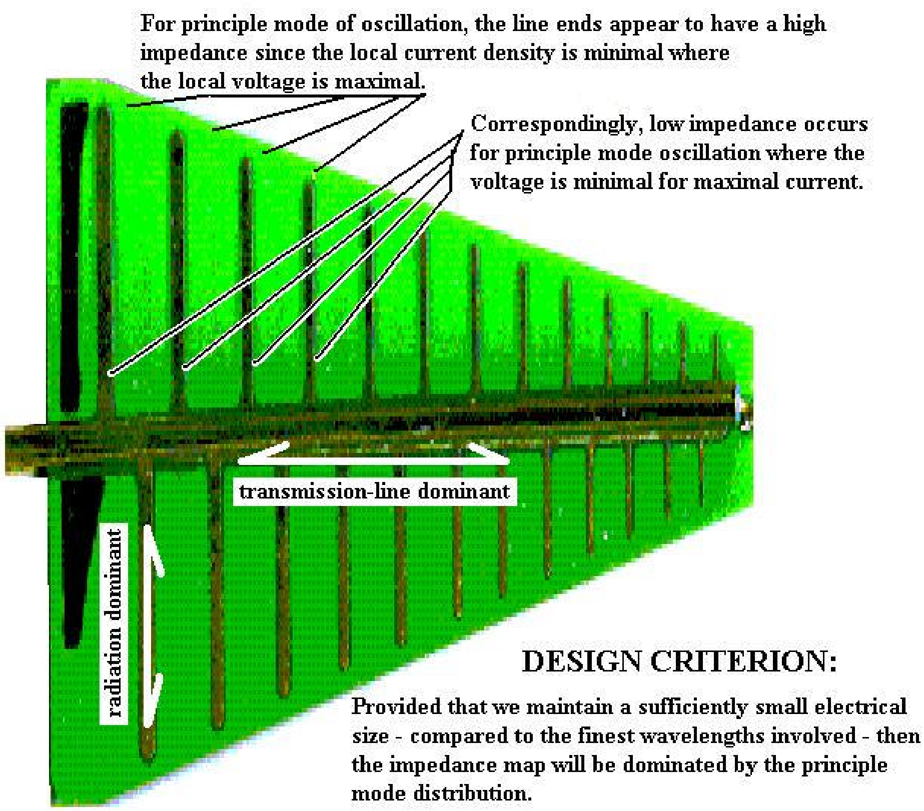


Figure 23 Study of impedance characteristics and transitions between radiant versus transmission-line character.

Then, from knowing the original wideband spectral response of the antenna, and by correlating our applied changes to alterations in the spectral response, initially by one-step-at-a-time, eventually in concert, we were able to establish patterns for understanding the effects resulting from our modifications. (see Figure 24).

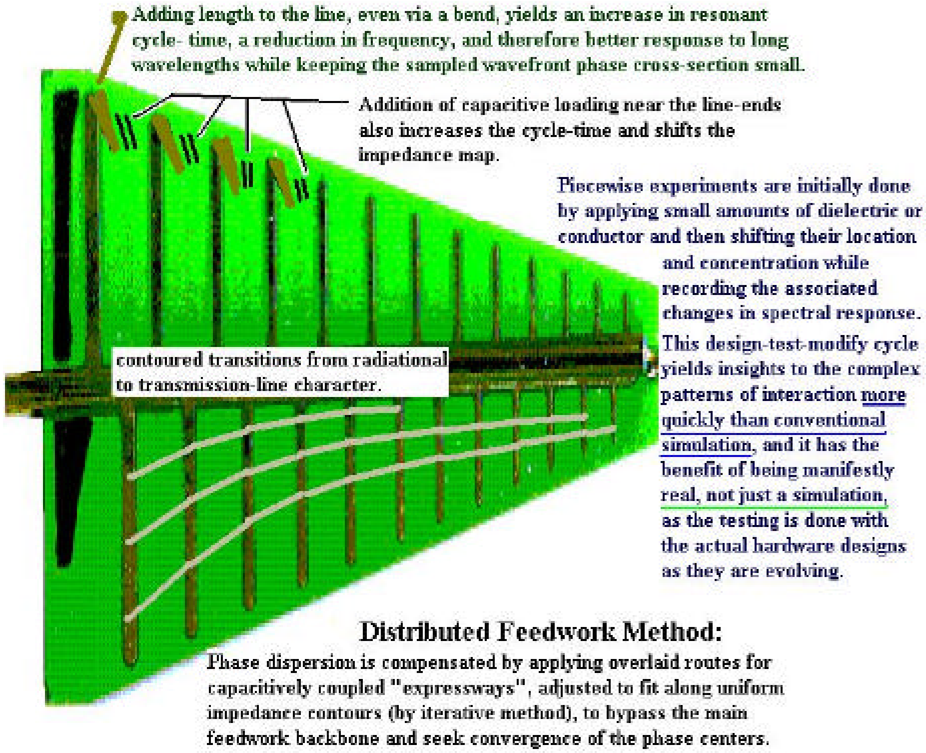


Figure 24 Piece-wise modifications to approach distributed feed-work phase-compensation design.

With the design lessons taken from our <u>piecewise modification study</u>, we decided to accelerate the evaluation process by applying electronic and optical methods to segue toward <u>smooth</u> reconfiguration of the antenna characteristics. (See Figure 25.)

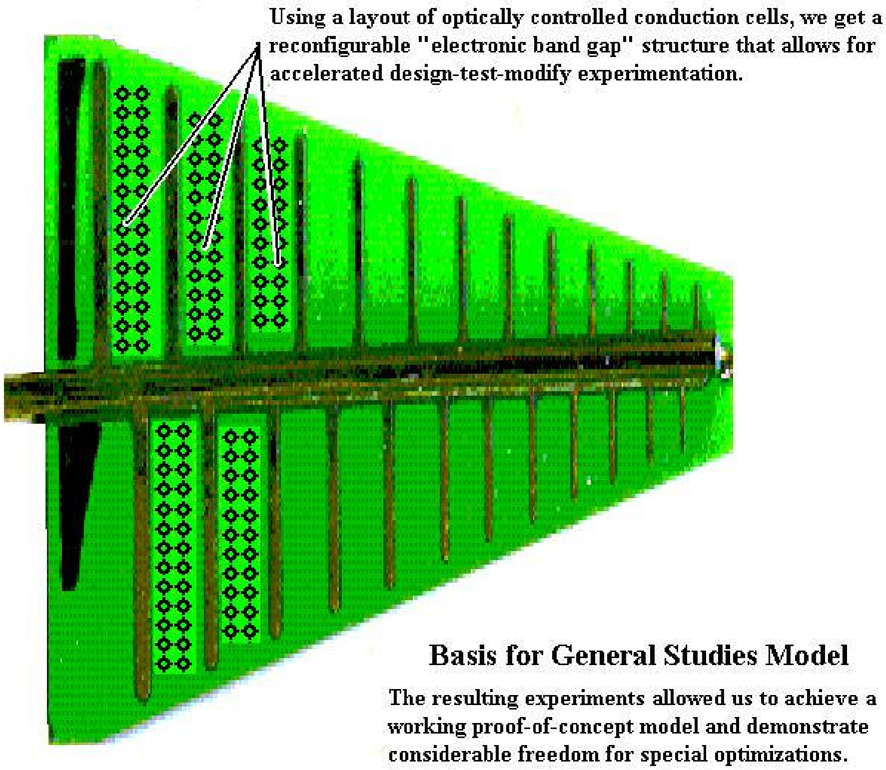


Figure 25 Initial optical control basis for general studies.

The following two references gave impetus to our most recent optical experimentation.

- EUROPEAN MATERIALS RESEARCH SOCIETY, E-MRS Spring Meeting 2004; May 24-28, 2004; SYMPOSIUM O - Thin film chalcogenide photovoltaic material "COMPARISION OF CdS FILMS DEPOSITED FROM CHEMICAL BATHS CONTAINING DIFFERENT DOPING IMPURITES", by M. Altosaar, K. Ernits, J. Hiie, et al

- E-MRS Spring Meeting 2002; June 18 - 21, 2002; SYMPOSIUM B -Thin Film Chalcogenide Photovoltaic Materials "ELECTRICAL AND OPTICAL PROPERTIES OF BORON DOPED CdS THIN FILMS PREPARED BY CHEMICAL BATH DEPOSITION", by Jae-Hyeong Lee, Woo-Chang Song, Dong-Gun Lim, et al]

3.5. Culmination – General Studies Model Basis: **CATSPAW**

After finishing the basic lessons with LPDAs, we adapted from the “Logi” concept of **non**-Log-periodic compact wideband antennas and then we created microstrip patch versions that operate with proximal groundplanes. From there, we applied our cross-coupled intermesh studies, and then converged toward EBG (electronic band gap) structures for the coupling systems. The resulting study-model (see Figure 26) established a <u>basis for methodical optimization</u> and was sufficiently reconfigurable so that we were able to demonstrate feasibility with a small-scale antenna consistent with the Phase-I goals:

- UWB spectral range, seeking a frequency range from 200 MHz-to-2 GHz;
  - we obtained a range from 250 MHz to ~3 GHz
- Phase linearity over channels of at least 200 MHz width;
  - we demonstrated phase linearity over spans as small as 750 MHz, up to 2 GHz
- Sensitivity
  - we obtained sensitivity comparable to EMI-testing grade of LPDA antennas.

The underlying skeleton of this EBG-layered “meshwork” is our own devised microstrip patch (with groundplane) cousin-relative of a “Logi” type of compact wideband antenna.

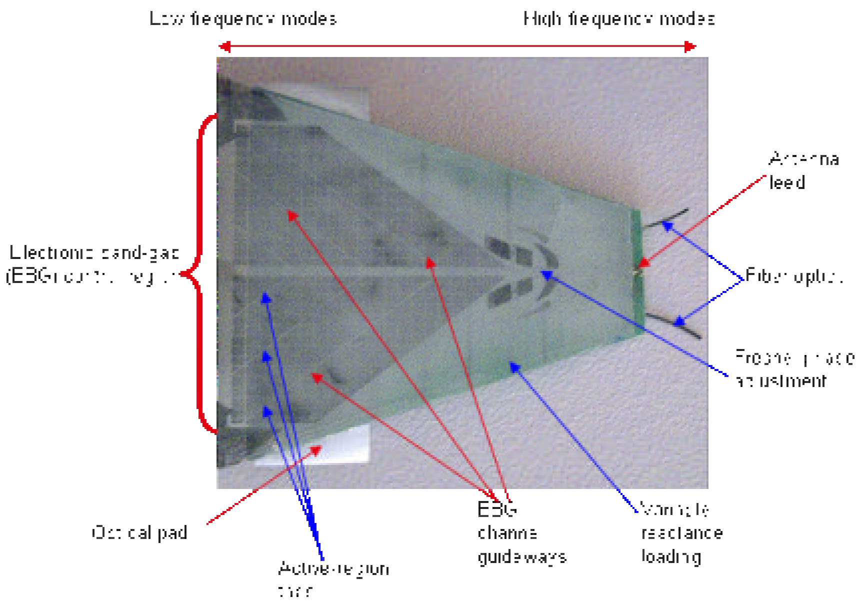


Figure 26 Anatomy of CATSPAW Antenna developed under the Phase I SBIR Program.

In achieving a <u>C</u>onfigurable-<u>A</u>perture <u>T</u>unable-<u>S</u>ubstrate <u>P</u>atch <u>A</u>ntenna for <u>W</u>ideband, we chose to name this prototype study-model as “CATSPAW”.

4. Considered Alternatives – Good Enough vs. Can Do Better

On the way towards developing CATSPAW we surveyed a variety of alternatives, the best of which are summarized below:

1) Stagger-tuning and coupling of overlapping resonances is exemplified in arrays of Yagi-Uda and Log-periodic dipole (LPDA) type. Common TV antennas are a variant of Yagi-Uda design that achieve a channelized selection in moderately narrow bands across an otherwise broad spectral range. The Log-periodic type emphasizes a broad spectral response per se. NOTE: These have been implemented in microstrip patch antenna form, and so they provided us with one of a few good starting points to derive our design from.

2) Elliptical *planar* dipole antennas can be fairly broadband and give fairly good phase behavior [26]. By judicious arrangement of the element contours relative to the antenna feedpoint, it is possible to minimize shifting of the radiantly coupled mode patterns so that the phase center stays relatively fixed through variations in frequency. NOTE: "Patch" versions of elliptical planar antenna are also good candidates for design reference, and appear to be "**good enough**" to satisfy this program's Phase-I expectations, yet they do not possess the tunability characteristics that we foresee as being needed for eventual use in sub-spectral and waveform adaptive applications.

3) Simple examples of contoured conduction are found in the extensions of "size-reduced" dipole arrays and in the forms of holed and cut slotted-edge patches. More elaborate examples include serpentine "wiggly" and rampart lines, among many others. In comparison with corresponding non-slotted non-convoluted structures, the contoured current paths extend oscillatory cycle time and thereby allow for lower frequencies to be achieved within compact structures.

To do better, to achieve ultra-broadband behavior within a microstrip antenna design, we extend upon the well-known stagger-tuning method by adapting from methods of contoured conduction (anisotropic resistivity, directs current along desired paths) and textured impedance (surface-wave guided filtering and directional coupling), which are recently receiving attention under the context of “band gap” designs [25].

5. Problems Faced and Solved with CATSPAW Prototype

In achieving proof-of-concept, the basic question was concerned with whether it was possible to produce an ultra-wideband patch-style antenna spanning a 10:1 frequency range and exhibiting phase linear characteristics. We confirmed this possibility with our study model, and there is considerable potential for further optimization.

5.1Phase Dispersion

The most daunting aspect of our design study involved the problem of waveform preservation, which requires a predominance of phase linearity over the spectral range.

Figure 27 below depicts the problem exhibited by typical phase dispersive systems; namely, the waveform that comes out of a system can be very different from the waveform that goes in, even though the frequency content is preserved. Unless the phase relations are also preserved, the results will yield distortion.

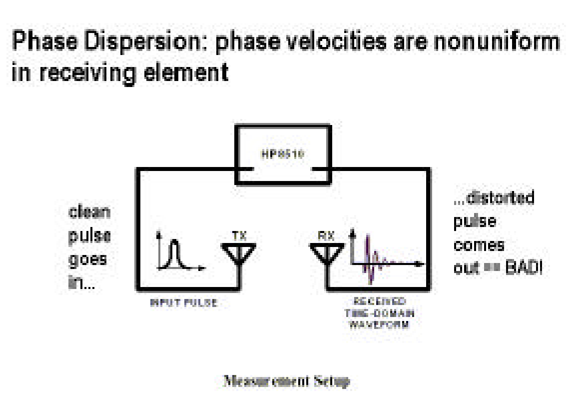


Figure 27 Waveform integrity and the phase dispersion problem.

Again, it is <u>not</u> enough to be UWB. LPDA antennas (see Figure 28 below) can be UWB, but they normally do <u>not</u> account for phase!

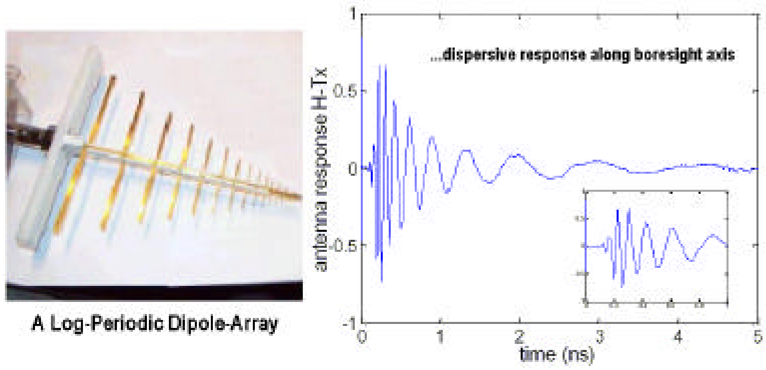


Figure 28 Log-Periodic Dipole Antennas (LPDAs) typically <u>do not</u> preserve waveforms of impulse type, though they can satisfy the bandwidth requirements of UWB performance.

5.2Relations between Spectral Response and Antenna Substructure

In our modeling, with confirmation from our hardware in-the-loop reconfiguration studies, we were able to begin correlating the geometrical complexes in the antenna structure with desirable features in the spectral response (see Figure 29).

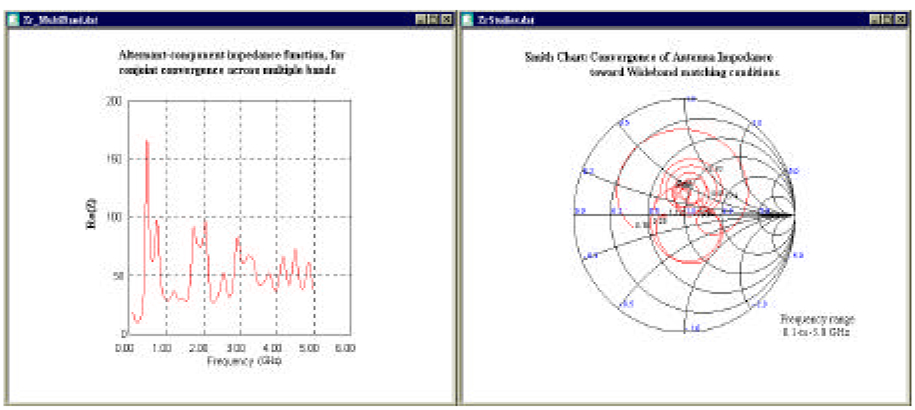


Figure 29 VSWR characteristic of an intermediate prototype antenna as a function of frequency is shown in the left figure. The right figure shows a Smith chart representation of the same data from which we evaluate and iterate our improvement process as we adjust the antenna's reactance structure. By combining the "complementary aperture"

version with this partial antenna, the composite structure approaches consistent impedance over the spectral range.

5.3Benchmark Tests Results

Figure 30 shows the *key* test results of our experimentation **BEFORE and AFTER tuning.** In the Smith charts shown here, the left image shows a moderate VSWR and impedance mismatch before tuning has been applied, while the right image shows the tuned reconfigured antenna as it achieves **good wide bandwidth impedance match and low VSWR** (better than 1.4:1 over the 1.0 to 2.0 GHz range).

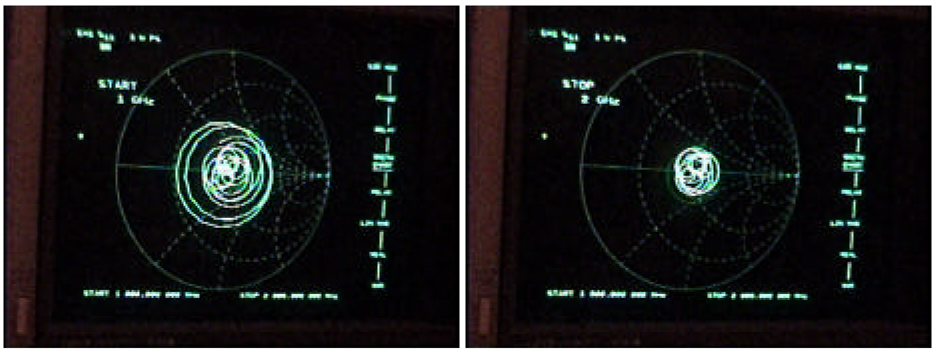


Figure 30 VSWR and impedance correction by dynamic reconfiguration method.

Figure 31 shows the change from an untuned state of **dispersive** character (left image) to a tuned reconfigured state (right image) of **Ultra-WideBand LINEAR PHASE.**

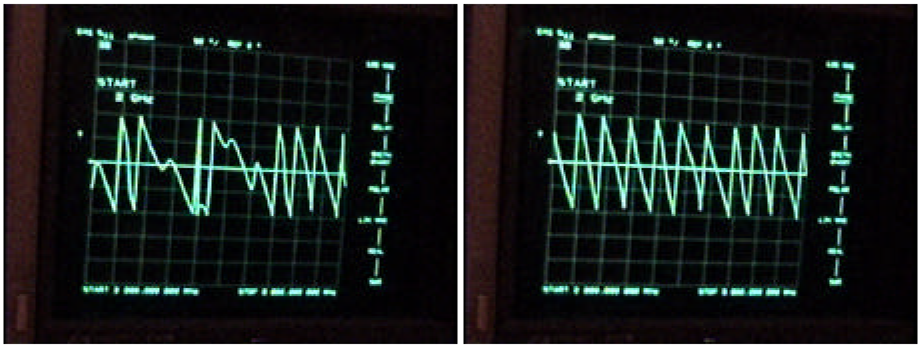


Figure 31 Demonstration of phase correction by tuning method. We have not-only achieved ultra-wide bandwidth with respect to impedance matching but also we have achieved minimally-dispersive phase across the band.

6. Achievement of Proof of Concept

During reconfiguration analyses, we achieved proof-of-concept in a study model that satisfies the Phase I goals and additionally demonstrates the potential for electronic steerability and sub-spectral channelization capabilities that are of interest for use in advanced radar systems. As a "Configurable-Aperture Tunable-Substrate Patch-Antenna for Wideband", we chose to name our antenna CATSPAW.

Review of the core experimental sequence: (basic hardware and controls)

The basis for our optical and electronic tuning studies is suggested back in Figure 19 (Electronic & photonic reconfiguration methods…") and Figure 25 ("Initial optical control basis for general studies"). Short of proprietary details, the experimental theme occurred as follows:

(1) T o establish reference behaviors as a basis of comparison, we started the electronic tuning study with varactors, and the optical tuning study started with photo-diodes (see Figure 19). The component parts used for these early experiments were common types readily available from Digikey. The controls simply consisted of variable voltage sources for the varactors, and a sequence of illumination methods: flashlights, LEDs, laser diodes, and fiber optics applied to the photo-diodes. The spectral response patterns were measured with an HP-8753 series Vector

Network Analyzer, using a 20dB directional coupler for connection with the antenna structures under test.

(2) Next, we varied the placement of the tunable components and, in a *coordinated* manner, we mapped the corresponding changes in the spectral response patterns. This provided us with a basis for comparison with more sophisticated arrangements.

(3) Next, we extended the tuning analysis by using multiple tuned elements and we mapped the corresponding changes in the spectral response patterns. To get the best information, we spread the placement of the components in proportion to their desired effects. Upon making sufficiently uniform patterns of the tunable components as addressable test-matrices embedded within the experimental antenna models we were able to eliminate the use of invasive test-probes and their associated effects of spurious reactances. This helped to greatly simplify the correlative analysis process.

(4) At this point, we learned how to go back and redesign the backbone metallization of the underlying antenna and feedwork structure, to serve as an improved reference point for further iterative experimentation and refinement.

(5) Finally we experimented with "anisotropic conductors" and "band gap" patterns to improve performance (bandwidth, compactness, impedance, dispersion and phase centering, tenability). By using "band gap" structures as overlying masks to determine the addressability patterns of photoconductive underlayers, we were able to make programmable "impedance surfaces" whose variation was correlatable with the changes of the antenna spectral response and dispersion characteristics. This gave us the basis for our programmable antenna of generally reconfigurable type.

7. Final Test Results, Design Considerations, Lessons Learned, and Conclusion

For final test results, beyond the benchmarks described earlier in section 5.3, we also had to prove that our antenna satisfies the Phase I condition of operability in proximity to a conductive groundplane. Here, Figure 32 shows our CATSPAW antenna resting on top of a metallic ground plane. The image on the right shows the display of the VSWR of the antenna setup without any tuning applied, yet nevertheless achieving a respectable average VSWR < 1.4:1 over a bandwidth > 400 MHz (centered around 1.6 GHz) which shows that we can more than satisfy the range needed for the channelization requirements of SARA's PING receiver (300 MHz widths).

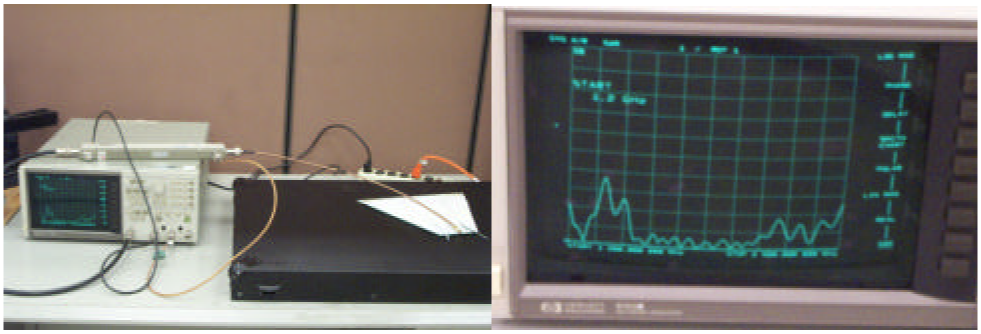


Figure 32 Working Phase I Proof-of-Concept, operating on metallic groundplane!

In summary, the Phase I CATSPAW design has demonstrated the following characteristics:

- **Instantaneous UWB Bandwidth (in non-tuned state):** CATSPAW satisfies the UWB requirement by attaining the ultra-wide instantaneous bandwidth of 250 – 3000 MHz with acceptable VSWR ~ 2:1 and small phase distortion. This is better in its upper frequency limit, compared to the solicitation goal of 2000 MHz, and is close to satisfying the lower limit of 200 MHz. (The latter factor can be dealt with simply by using a somewhat larger 'out-size' printed-circuit board and/or a higher permittivity base substrate; albeit at escalated expense).

- **Impedance match/VSWR**: By moderate tuning of the antenna, the prototype achieves a good VSWR of 1.4:1 signal level over the large sub-band ranges (400 - 1000, 1000 - 2000, 2000 - 3000 MHz), and excellent VSWR of < 1.2:1 (or 99.2% clean) across band widths of at least 400 MHz. This nicely satisfies the requirements necessary for the channelized receiver of SARA's PING system.

- **Dispersion/Phase linearity**: With moderate (but not optimized) tuning, our prototype achieves excellent phase linearity over the wide sub-bands of 400 - 1000, 1000 - 2000, and 2000 - 3000 MHz. The phase linearity is proportionately cleaner for the smaller 400 MHz bandwidth of the channelized receiver.

- **Configurability**: we have clearly demonstrated the configurability of the CATSPAW antenna using various tuning methods (electrical and optical). This tuning capability was explored for two reasons: (1) to help accelerate the parameter optimization studies and (2) to anticipate eventual needs of Phase II adaptations. In Phase II, an optimized antenna will meet UWB requirements while tuning function will primarily be used to switch from UWB operation to various sub-band operations and for beam steering.

7.1. Design Considerations - Fabrication Complexity/Simplicity of our Approach

The CATSPAW prototype antenna is a multi-layered "patch"-derived printed antenna in which electronic and optical reconfigurability was achieved for controlling phase dispersion and VSWR/surface impedance. As was questioned in our AFRL interim meeting, the visual appearance of the antenna seems to be complex since it has small (fraction of wavelength) features. However, the fine structural features are simply versions of "electronic band gap" structure that we used to correlate configuration changes together with spectral response.

Conveniently, our antenna is fabricated using standard "printed circuit board" techniques that are well understood and established. The fine resolution of the tuning layers was appropriate for this prototype analysis to help determine the patternings that optimized configurations may employ during Phase II. Beyond that, the fabrication of this tuning layer is significantly easier than the alternative of a multi-bus gridded array of discrete opto-electronic components.

In comparing our designs, which explored the use of photoreactive and electronically variable substrates, versus other competing designs that make use of MEMs (micro-electromechanical switches) or discrete opto-electronic (OE) components, the following table clearly shows the increased complexity of the MEMs/OE alternatives:

Photoreactive Substrate	**MEMS/OE Alternatives**
No additional conductive traces; just a few optical guides needed, and fortunately they enjoy minimal interference and crosstalk	Require a multiplicity of conducting circuit traces that have to be accounted for against possible interference effects in reception pattern
Fine resolution	Comparatively coarse granularity
EMP and Rad tolerant	EMP and Rad damage susceptible
Comparatively inexpensive	Significantly greater cost

Clearly, our reconfiguration approach has significant advantages over a MEMS/OE approach since it avoids the complexity of attaching MEMS/OE components and eliminates the galvanic interference effects that derive from the MEMS/OE metallization and power-supply traces.

Finally, we have recently found reference (announced to appear in PIERS 2005) to a comparable design study performed on a conformal Archimedean Spiral antenna to achieve phase linear correction (see Bibliography)[1]. Such a study validates our more general approach for configurable dispersion correction.

7.2. Lessons Learned

Among alternatives that we considered, it seemed that "spiral" type antennas could be potentially good candidates since they can achieve considerable ultra-wide bandwidths. However, they tend to be either omni-directional or weak in directive gain, while it can be helpful for the UWB impulse antenna to have some directivity especially if such can avoid damage from an impulse transmitter by looking in the "away" direction (listening only for retro-directed returns). Hence we designed our antenna to have a default configuration with directive gain (~7 dB gain), so that it also can localize a target just by lobe-sweeping triangulation, in addition to fancier steering methods.

To solve for dispersion, we know that minimization of antenna element "electrical size" is the best way to go for a well-populated array design. While electrical sensitivity decreases on a per-element basis, yet the dispersion reduces in proportion, and better yet, the signal-to-noise ratio improves as the square-root of the element count in the array. But since spectral windowing is also important for advanced target analysis, and the eventual application context may limit the array size, then we chose the option of solving for dispersion by means related to our approach to

[1] Phase-correction of an archimedean spiral antenna by capacitor-loading pattern… Announced to appear in PIERS-2005, "A Conformal Archimedean Spiral Antenna for Ultrawide-band Systems", Qi Wu, Ronghong Jin, and Xiaojing Huang.

spectral shape selection. Thereby we implemented tunable reconfiguration methods, and we learned that we could solve for dispersion and achieve some control of receptive directionality within our antenna at the same time. Concurrently, we also learned that we could modify the general impedance behavior of the antenna through similar means. Taken altogether, these reconfigurable functions provide a basis for developing an ultra-wideband steerable impulse receive antenna array.

Our approaches to reconfigurable tenability include electronic, optical, and electro-optical methods. Each method has certain advantages that are relevant depending on context. The electronic methods tend to be good for handling high power, and the hybrid electro-optic methods tend to enjoy higher-speeds of control, albeit at greater complexity and added expense. The optical methods of control enjoy a high-degree of immunity relative to radio-frequency interference, but they tend to be somewhat delicate relative to power-handling capability. Since the initial design context involved only "receive" mode antennas, then limitations to low-power signals was not a problem. However, we are looking ahead to the possibility of "transmit" mode antennas being developed upon a related basis. So, while we continue to be interested in the usefulness of optical reconfiguration methods, we are currently favoring hybrid electro-optical methods to allow for the potential of dual transmit and receive functions in support of waveform adaptive methods of advanced radar operations.

7.3. Conclusion, leading to Phase-II Recommendations

Since an ultimate type of UWB-impulse antenna would be in the form of a "true-time-delay" steerable array, then our Phase 1 investigation concludes with immediate follow-on goals of yielding separate modular forms of the associated key enabling technologies adaptable for use in other systems:

1) waveform-preserving true-time-delay signal transmission components ;

2) dispersion-correction components;

3) programmable spectral impedance matching components.

8. Phase II Recommendations

AFRL is developing a wide range of applications for its UWB-*impulse* radar program (also referred to as PING). A number of these applications are calling for the development of conformal receive antenna arrays capable of “true-time-delay” (TTD) beam steering. Upon completion of our Phase I technical activities, AFRL invited us to submit a Phase II proposal to develop and demonstrate the necessary enabling technologies for true-time-delay beam steering for UWB-impulse antenna arrays.

Using the technologies developed and demonstrated under this Phase I SBIR program, we recommend the following Phase II program objectives, in support of the development of a true-time-delay steering impulse receive antenna:

1. Developing electronically reconfigurable True-Time-Delay (TTD) signal line

2. Developing electronically reconfigurable Phase-Dispersion and Aberration Corrector

3. Developing electronically reconfigurable Impedance / Frequency / Bandwidth Tuner

4. Demonstrating integration of above-listed functions in a single antenna element

5. Demonstrating integration of above listed functions in a TTD steerable array

The first three items are focused on developing the enabling technologies and the last two are focused on demonstrating the technologies.

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- Per-Simon Kildal, Wen Xun Zhang, Ting Hua Liu, and Jian Yang STUDY OF SPIRAL ANTENNA ON THREE PBG GROUND PLANES: ARTIFICIAL MAGNETIC CONDUCTOR, SOFT SURFACE AND HARD SURFACE ; 24th ESTEC Antenna Workshop on Innovative Periodic Antennas: Photonic Bandgap, Fractal and Frequency Selective Structures

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