Updating the Multiband Reconfigurable Synthetic Aperture Radar Antenna

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Abstract **– During the previous ESTO Conference, the author introduced an adaptive array of microstrip antennas, the operating frequency, beam geometry and steering of which were to be accomplished by electrostatic means. QorTek is presently investigating the application of new innovations from the field of dielectric materials that would enable large dynamic adjustment of operating characteristics through simple application of DC tuning voltages. Although the dielectric materials are still emerging as commercially available items, our technology partners at two major universities have been working hard to provide us with the materials necessary to implement this advanced design. With their assistance and insights, we are inching closer to achieving a reproducible design that would enable NASA to integrate multiple diverse missions into a single antenna design suitable for spacecraft or high altitude aircraft structural integration.**

I. INTRODUCTION

It has been previously shown[1] that microstrip patches serve well as efficient antenna elements when longitudinally excited, such as by microstrip transmission lines, coplanar waveguides, and the like. The resonant frequency of such an antenna element is determined by:

$$f_o \simeq c / [2L (\varepsilon_r^{\ 1/2})] \qquad (1)$$

where f_o = resonant frequency in Hz
c = the speed of light = $3 * 10^8$ m/s
L = the physical length (in meters) of the patch element or resonator
and ε_r = the permittivity or dielectric constant of the substrate, relative to free space.

Thus, the operating frequency of a patch antenna element or dielectric resonator varies inversely with the square root of the relative permittivity of its dielectric material. Such antennas generally operate efficiently over a narrow range of frequencies, and have a finite radiation pattern [θ, ϕ] limited by the quality factor Q, or the dissipation factor δ, of the dielectric material.

It is common practice to assemble multiples of such antenna elements on a common substrate, interconnected so as to form a phased array to achieve numerous performance improvement objectives. As the number of properly phased array elements increases, the radiation pattern [θ, ϕ] decreases (a desirable outcome in most applications), while the operating frequency range diminishes.

II. VARACTOR TUNED TEST ARRAY

The proposed design will incorporate patch antenna elements etched or deposited onto new dynamically tunable dielectric materials. These materials exhibit the property of tunable permittivity. That is, in the presence of an applied electrostatic field, their relative permittivity can be made to vary locally over a wide range of values depending upon the intensity of the applied field (or upon the potential of the electric charge generating such field). Since we have seen (Equation 1) that resonant frequency varies inversely with the square root of the relative permittivity of a given dielectric, it can be expected that such dynamic dielectric properties will cause a patch or dielectric resonator antenna, or array of such patch or dielectric resonator antennas, to be frequency tunable over a wide range, which does not diminish with the addition of multiples of elements.

When multiple antenna elements are combined into a phased array (see Fig. 1), the interconnecting structure is generally composed of transmission line elements of fixed characteristic impedance, such as in microstrip or coplanar waveguide, with each transmission line element tuned in length to present an integer multiple of one-quarter of a guide-wavelength ($\lambda_g/4$) on the substrate in question. The purpose of said transmission line elements is to divide power uniformly between individual antenna elements in the transmit application, and to combine power uniformly from individual antenna elements in the receive application, while presenting a uniform impedance match throughout the system.

According to basic electromagnetic theory as articulated by Maxwell's Equations, the electrical length of a transmission line etched or deposited on a given substrate varies from its physical length by the velocity of propagation of the wave along the transmission line, relative to that of waves in free space. In terms of wavelength at a given operating frequency:

$$\lambda_g \simeq \lambda_o / (\varepsilon_r^{\ 1/2}) \qquad (2)$$

where λ_g = guide wavelength,
λ_o = free-space wavelength,
and ε_r = the permittivity or dielectric constant of the substrate, relative to free space.

Thus, the physical dimensions of microstrip or coplanar transmission lines used to combine multiple antenna elements are both frequency dependent and constrained by the relative permittivity of the substrate on which they are etched or deposited.

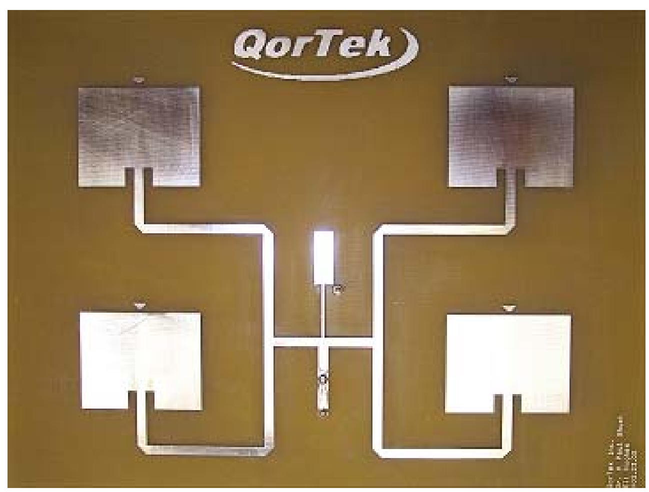

Figure 1
Typical microstrip phased array antenna

[1] Shuch, H. Paul, Multiband Reconfigurable Synthetic Aperture Radar Antenna, Paper B1P1, ESTC 2004 Proceedings (CD), Palo Alto CA, June 2004.

In the present design's first iteration, tunability and beamforming were achieved by capacitively loading the individual patches of a microstrip array, thus varying their resonant frequencies independently, to achieve steering through beam squint. Epitaxial silicon voltage variable capacitors (varactors) shunting each patch to ground were mounted to the pads just above each of the four antenna elements seen in Figure 1, with tuning voltages applied through a DC bias tee visible at the center of the board. Using four such tunable sub-arrays tuned in quadrant architecture, limited frequency tuning and beam steering were achieved, as documented in Figure 2.

As an alternative to capacitive loading, it is desirable for the physical length of the individual transmission line elements to be made to vary across the face of an array, so as to modify the geometry of the radiation pattern [θ, ϕ] in some application-specific way. Since the physical length of a transmission line etched or deposited on a given substrate is fixed and invariant, and its electrical length is dependent upon the relative permittivity of the dielectric, it can be seen that a fixed radiation pattern will result from such etched or deposited transmission line networks. Pattern adjustment or beam steering of phased array antennas will therefore require the addition of active or passive switching elements, to modify the performance of the transmission lines in some way.

To achieve improved electrical tuning, the QorTek design contemplated the ability of new, dynamically tunable dielectric materials, as described above, to allow the guide wavelength λ_g of the individual transmission line elements to be independently adjusted, through the mechanism of locally varying the relative permittivity upon which each individual transmission line element is etched or deposited, thus permitting the beam geometry and radiation pattern [θ, ϕ] of an antenna array to be dynamically modified by the application of external DC potentials. This tunability would allow us to achieve a wide variety of mission objectives. The most promising candidate material to date for such tunable substrates include Barium Strontium Titanate (BST) and Barium Zirconium Niobate (BZN), which we hope will improve upon the performance achieved with tuning varactors. Because such materials typically suffer from poor thermal stability (that is, dielectric constant varies significantly with temperature), special processing techniques are being explored, as described in Section V of this paper.

16 patch varactor-tuned array on FR4 circuit board

Center Frequency	=	2.4 GHz		
Bandwidth	=	60 MHz	=	2.5 %
Loaded Q	=	40		
Pre-bias	=	1 VDC		
Tuning Range	≃	300 MHz	=	12.6 %
		e-field	h-field	
Beamwidth	≃	15	10	deg.
Steering Range	≃	20	13	deg.

Compact range, tested at mutual Rayleigh distance

Figure 2
Preliminary test results, capacitively tuned 16-element array breadboard

III. DIGITAL TUNING AND CONTROL

In order to vary independently the tuning voltages applied to the varactors attached to the individual antenna elements, allowing maximum antenna steering and tuning agility, a digital controller (Figure 3) has been designed and fabricated. This digital tuner uses a Cygnal C8051F236 microprocessor to receive commands from the control software, and translates those commands into appropriate control signals for a 4-channel, 16-bit DAC subsystem. A Universal Serial Bus (USB) interface is provided by a CP2101 USB interface controller. The CP2101 is a convenient device that translates native USB bus logic into a simple asynchronous serial interface for the Cygnal microprocessor. Graphical User Interface (GUI) software sends command packets to the CP2101 controller, which then translates this information into asynchronous serial data that can be more easily decoded by the hardware on the C8051F236. Once the firmware in the microprocessor receives a command packet, it sends appropriate data to the 16-bit DACs (DAC8532) via an SPI interface. The output of the DACs are then amplified and buffered by simple op-amp circuitry which transmits the tuning potentials to the tuning elements in the antenna. The current hardware allows for four quadrant control, but it can easily be paralleled to provide any number of control channels with appropriate firmware changes. Hardware and software scaling to an arbitrary number of channels is presently being investigated.

Figure 3
Digital Array Controller

IV. GRAPHICAL USER INTERFACE

Figure 4 shows a Graphical User Interface (GUI) to allow testing of the prototype array under user commands input via a laptop computer. The current GUI revision incorporates three different graphical mechanisms for performing 4-quadrant beam steering and frequency tuning. The first, and lowest level mechanism, allows the user to individually tune each one of the quadrant tuning potentials via a graphical slider and text input box. These controls are seen in lower left hand quadrant of the GUI screenshot. The second mechanism for tuning control is in the upper left hand quadrant of the GUI screenshot. There are three slider controls that provide authority over X steering, Y steering and antenna center frequency. When the user modifies the steering and/or frequency controls, the software calculates the appropriate four tuning potentials.

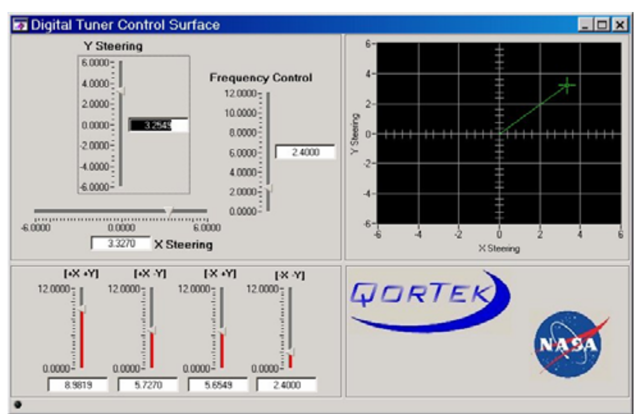

Figure 4
Synthetic Aperture Radar Antenna Graphical User Interface

The last tuning mechanism is provided via a graph/cursor control shown in the upper right section of the GUI screenshot. This control allows the user to drag a cursor about a X-Y plane to set the X and Y steering settings.

Because there are three ways of controlling the tuning potentials, there is a pre-defined control priority funnel within the GUI software. At the lowest level of this control funnel are the 4 individual tuning potentials ([+X +Y] , [+X –Y] , [-X +Y] , [-X –Y]). All tuning changes made on the control surface map down to these four tuning potentials and are what are ultimately get transmitted to the tuning hardware via the USB interface. Changes made to the X and Y steering controls are mapped to the cursor on the graph control and then are funneled to the four tuning potentials. If the cursor is manipulated, its X and Y values are sent to the X and Y control sliders and then funneled to the four tuning potentials. As the frequency slider is manipulated, its value is mapped to the four tuning potentials as well. It is important to note that all changes made a sent to the tuning hardware in real-time. The control update loop time in the GUI algorithm is approximately 5mSec.

V. MIGRATING TO TUNABLE MATERIALS

A key feature of the proposed design is that antenna element resonances will be electrically tuned. In the first breadboard, this was accomplished with semiconductor devices. As previously noted, the ultimate design seeks to employ tunable dielectrics to accomplish improved performance. As seen in Figure 5, the curvilinear line represents the performance of the epitaxial silicon tuning varactors used in the 16-patch breadboard first demonstrated. The nonlinearity in capacitance response over voltage, which is common of semiconductor devices, is evident. The linear curve shows an ideal, C/V response over the desired range of tuning voltages and device capacitances, which we hope the proposed tunable materials (BST and BZN) should be able to approach. This curve has been provided to our subcontractors at both NCSU and PSU, as a design goal for the tunable capacitors now being fabricated, for testing at QorTek during the coming months.

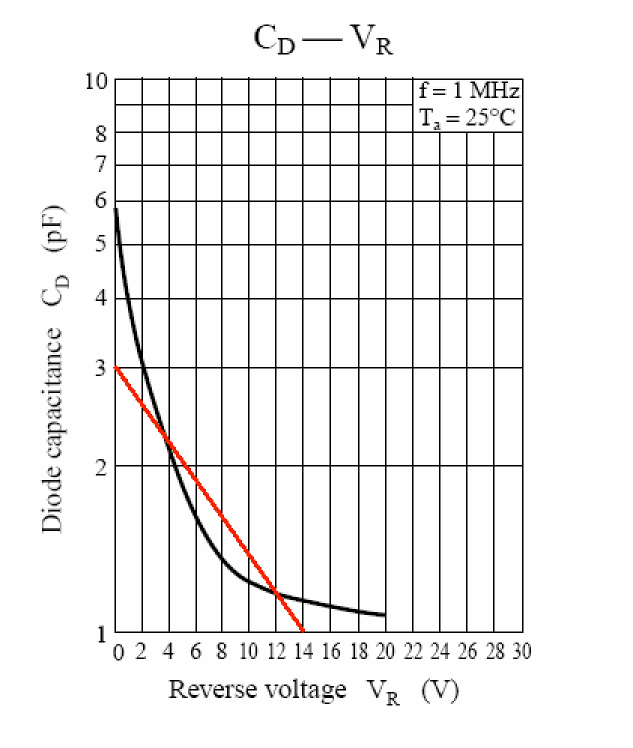

Figure 5
Capacitance vs. applied potential for varactor diodes (curved line), as compared to the desired C/V relationship for tunable substrates (straight line).

Unfortunately, the required materials are currently in the developmental stage, and commercial availability in production quantities may still be some months or years away. Thus, it could be said that QorTek is designing antennas to be fabricated from Unobtanium! In order to provide the required materials in sufficient quantities to more fully test this design concept, two competing process technologies are being explored.

The relative permittivity of Barium Strontium Titanate (BST), one of the most popular and promising tunable dielectric materials, suffers from extreme temperature dependence, with the peak in the permittivity curve varying with temperature as a function of stochiometry. That is, varying the ratio of barium to strontium shifts the temperature at which a permittivity maximum occurs, as illustrated in Figure 6. Our colleagues at North Carolina State University are experimenting with a solution involving a micro-engineered dielectric stack, to reduce the material's temperature dependence. If a layered sandwich of three different BST compounds, each with a different Ba/Sr ratio, is produced, superposition suggests a resulting reduction in the material's temperature dependence, as illustrated in Figure 7.

The results achieved to date with a two-layer stack, as seen in Figure 8, suggest that this strategy will prove useful in producing BST capacitors for tuning and steering the SAR antenna in the present project. Work toward physical realization of such components is currently underway.

An additional challenge facing our NCSU partners is the range of capacitances required in the present application. For antenna tuning in the GHz range, the values of the required capacitors will typically be in the hundreds of femtoFarads. However, most ferroelectric films at thicknesses on the order of 1 um have capacitance densities on the order of several femtoFarads per square um. For capacitors of practical dimensions, such materials produce capacitances several orders of magnitude too high (resulting in capacitive reactances so low as to effectively short out the antenna elements for which they are intended to serve as shunt tuning elements).

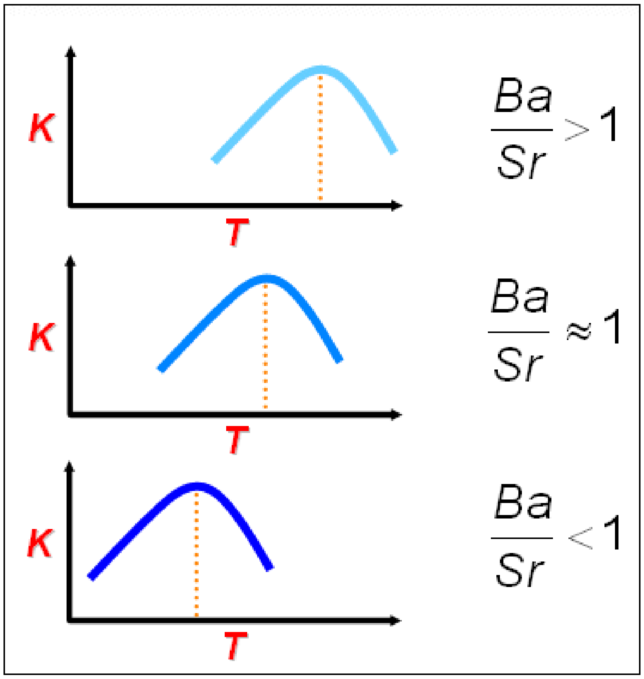

Figure 6
BST compositions of varying stociometry produce different temperature peaks in their relative permittivity curves. This temperature dependence of the materials will, if unmitigated, degrade their performance as tunable dielectrics for SAR antenna use.

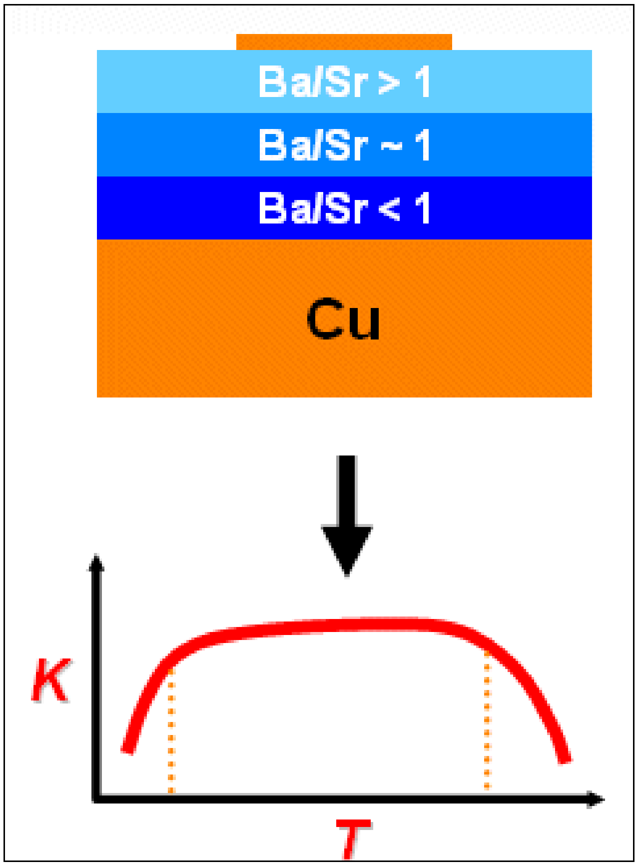

Figure 7

Nano-engineered dielectric stack, involving ferrotunable materials of three different stociometries, promises to reduce the temperature dependence, permitting BST tuning capacitors to be fabricated for the present application.

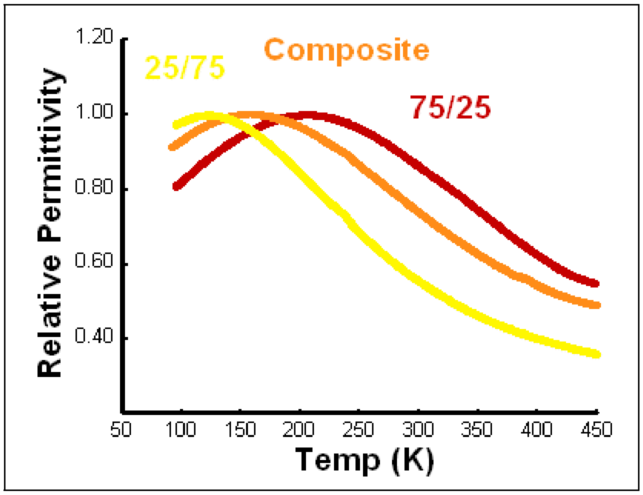

Figure 8

Composite performance of a two-layer BST stack does indeed indicate reduced temperature dependence, as illustrated by the broadened peak in the central curve.

NCSU's solution to the size problem is depicted in Figure 9. It involves a physically large capacitor with oversized electrodes, convenient for assembly and wire bonding, but exhibiting low capacitance, accomplished by minimizing its plate areathrough use of a field polymer above a small BST window. Fabrication of the first such test capacitors is currently in progress.

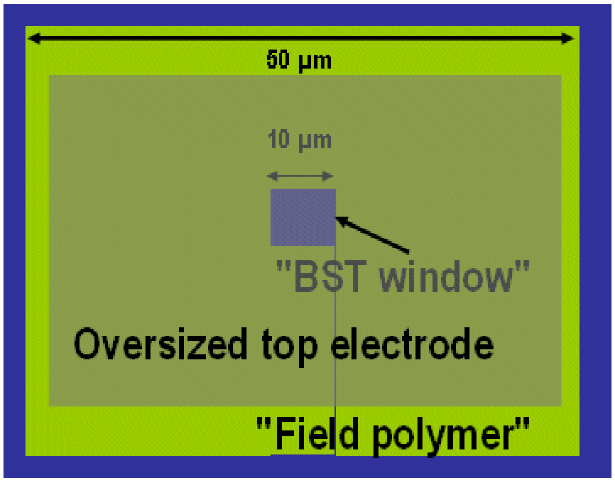

Figure 9

Low-capacitance tuning element fabricated from BST, of a physical size compatible with installation as a tuning element on the proposed SAR antenna, is accomplished through windowing of a field polymer, allowing small plate area and large electrode area.

Another team of materials scientists, working at the Pennsylvania State University, is independently exploring an alternative approach to providing the present research with the required electrostatically tunable capacitive elements. In order to circumvent both the temperature dependence and the high processing temperatures of BST, the PSU group has chosen to explore Barium Zirconium Niobate (BZN) as a tunable dielectric material.

It is desirable to deposit dielectric films on flexible substrates, e.g. metal foils or polymeric lamina, for future low cost, light weight, flexible synthetic aperture radar (SAR) antenna. In addition, we desire the dielectric films applied for the SAR antenna to show high dielectric tunability, low losses, and low temperature coefficient of capacitance (TCC). Ferroelectric materials are, however, very temperature sensitive. Recent studies showed that Bi1.5Zn0.5Nb1.5O6.5 pyrochlore films exhibit excellent dielectric properties, i.e. dielectric constant close to 180,low losses, and a dielectric tunability larger than 30%. Thereby, Bi1.5Zn0.5Nb1.5O6.5 pyrochlore films are a good candidate for SAR antennas. Unfortunately, the Bi1.5Zn0.5Nb1.5O6.5 pyrochlore films fabricated by either metalorganic deposition (MOD) or sputtering must be annealed at temperatures of at least 600°C, which makes the integration with polymeric substrates problematic.

The process being explored at PSU seeks to achieve high dielectric tunability, low losses, and low temperature coefficient of capacitance through low-temperature KrF excimer pulsed laser annealing (PLA) of BZN on pyrochlore films. In addition to the stated electrical properties, the proposed solution promises to offer a high degree of flexibility, desirable for the fabrication of conrormal and deployable space SAR antennas.

Results achieved by PSU to date are depicted in Figures 10 and 11. It will be noted that a wide dielectric tuning range has been achieved, with thermal stability superior to that which has been observed with BST. Fabrication of tunable capacitors for performance testing in a breadboard SAR antenna array is currently underway.

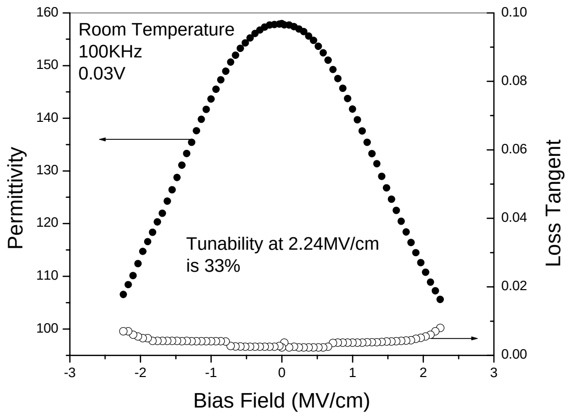

Figure 10
Permittivity and loss of PLA BZN/Pt/Si films as a function of applied DC field.

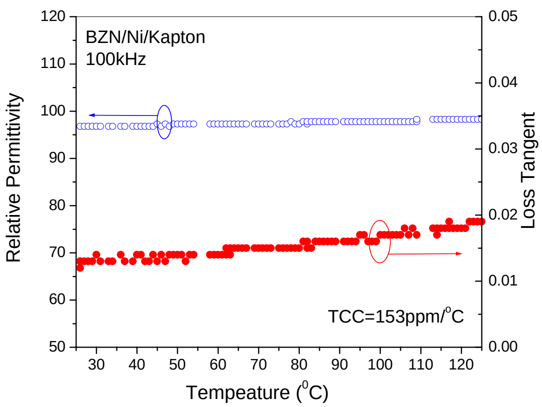

Figure 11
Permittivity and loss of BZN films deposited on Ni coated Kapton® as a function of measuring temperature.

VI. Technology Demonstrated

Now midway through year three of a technology demonstration project for the NASA Earth Science Technology Office, QorTek has demonstrated beam steering and tuning with a sixteen-patch breadboard array (see Fig. 12) on a conventional fiberglas-epoxy substrate. Since the advanced ferrotunable materials required for an active substrate are not yet available in reasonable quantities, tunability and steerability were initially tested by loading each of the patches with a shunt voltage-variable capacitance diode (varactor), as previously described.

Preliminary testing has validated the quandrant steering and tuning concept, the digital controller hardware, software and firmware, the USB interface, and the Graphical User Interface (GUI) developed for array control. In the laborarory, this test antenna has exhibited a 2.5% instantaneous bandwidth, a 12.6% tuning bandwidth, 40 degrees of total e-field steering, and 26 degrees of total h-field steering in S-band. Integration of advanced tunable materials, a main thrust of the present project, remains to be demonstrated. During the next six months, depending upon the availability of suitable materials, we intend to replace the varactors with electrically tunable variable capacitors, significantly increasing both tuning range and angular beam steering capability. Ultimately, when either BST or BZN becomes available in production quantities, we can anticipate a full implementation of a tunable, steerable SAR antenna, monolithically fabricated on a large-area tunable substrate, for aircraft and spacecraft applications across two or more octaves of the microwave spectrum.

VII. Applications

The following NASA Earth Science Technology Office programs represent potential candidate applications for the technology being developed herein:

- Global Topography Mapping Mission – provides high resolution, digital topography mapping (L-band SAR)
- Dual Frequency, Multi-Polarization Global Mapping SAR Mission – measuring biomass and soil moisture, providing high resolution regional-scale measurements (L and X band SAR)
- Ocean Phenomenology Mission – to study low-wind wakes and high-wind mountain waves that form in the atmosphere downwind of rugged islands (C and L-band SAR)

In addition to these specific ESTO missions, the proposed technology offers promise in the areas of:

- Satellite Television Transmission and Reception
- Mobile wireless networking
- Aerospace Telemetry
- Remote Sensing
- Weather Monitoring
- Air Traffic Control
- Missile Defense
- Electronic Countermeasures
- Command, Control, Communications & Intelligence

VIII. Conclusions

The combination of advanced microstrip patch antenna designs, quadrant steering and tuning architecture, and newly emerging electrically tunable materials promises to enable the development of large-scale, flexible, steerable and frequency-agile antenna arrays, for use in aperture synthesis, scanning radar, adaptive telecommunications, and a host of related aerospace and commercial applications. During the final months of this three-year contract, QorTek plans to integrate the various elements of the design into a small-scale demonstrator system, achieving Technology Readiness Level 4.

Acknowledgments

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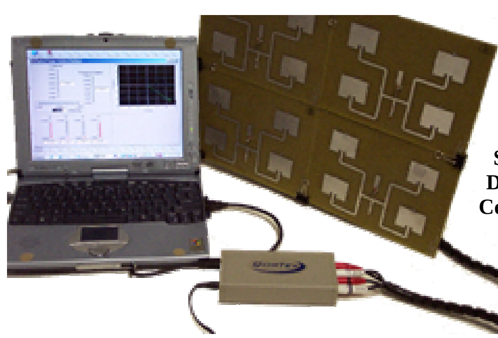

Figure 12
SAR Test Antenna System under Digital/GUI Control