Multiband Reconfigurable Synthetic Aperture Radar Antenna

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***Abstract* -- This paper describes the development of an adaptive array of microstrip antennas, the operating frequency, beam geometry and steering of which are accomplished by electrostatic means. QorTek employs new innovations from the field of materials science to permit dynamic adjustment of operating characteristics through the application of DC tuning voltages. Such adaptive arrays will reduce cost, weight, and complexity, while improving reliability in such diverse fields as ground and space telecommunications; synthetic aperture radar; satellite remote sensing; weather monitoring; air traffic control; missile defense; electronic warfare; and military command, control, communications, and intelligence applications.**

I. INTRODUCTION

It has long been known that microstrip patches can 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. THE TUNABLE, STEERABLE PATCH ARRAY

This design incorporates 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.

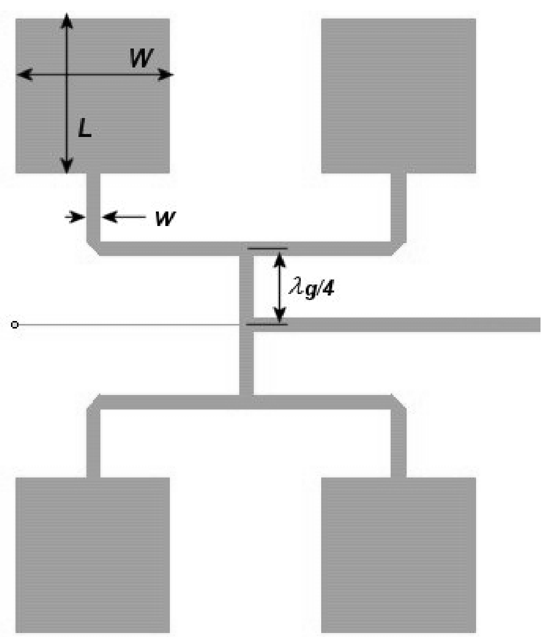

Fig. 1. Typical microstrip phased array antenna.

Often the physical length of the individual transmission line elements is 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 electrical tuning, the QorTek design capitalizes upon 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 will allow us to achieve a wide variety of mission objectives. The most promising candidate material to date for such tunable substrates is barium strontium titanate (BST), which exhibits a typical variation in permittivity over applied potentials as seen in Fig. 2. Because such materials typically suffer from poor thermal stability (that is, dielectric constant varies significantly with temperature), other such ferrotunable materials are also being explored.

III. Quadrant Tuning

It has been shown that changing the relative permittivity of the substrate below a patch antenna element varies its resonant frequency. Thus, if all patches in an array are tuned in parallel, the overall resonant frequency of the antenna changes. However, if dielectric tuning is applied locally, it is possible to vary the beam geometry of the resulting antenna pattern. Typically, such control mechanism would require a separate tuning voltage to be locally applied to the substrate below each array element. For large arrays of x by y elements, the required number of individual tuning signals (x * y) can be quite large. The present design seeks to maximize patterning flexibility while minimizing the required number of individual control signals.

Especially interesting is the case where antenna elements on opposite sides of an array are voltage-tuned differentially, so that the patches on one side of the array resonate slightly higher, and those on the other side of the array slightly lower, than the intended operating frequency. In this case, the directionality of the antenna array varies, as the detuning of opposite elements causes the beam to squint. This property can be exploited by tuning the antenna array by quadrants, as shown in Fig. 3. Differential application of tuning voltages in the X plane will cause the beam to sweep or steer in azimuth, while differential application of tuning voltages in the Y plane will cause the beam to sweep or steer in elevation. By applying tuning voltages to entire quadrants rather than individual elements, simultaneous azimuth and elevation steering can be accomplished purely by electrical means. Beam deflections of just a few degrees have been experimentally demonstrated from a first-generation planar antenna array breadboard, with tens of degrees considered entirely achievable as the technology matures.

IV. Control Electronics

The application of the differential control voltages necessary to steer a patch antenna array can be readily accomplished by analog means, using the op amp voltage combiner circuit shown in Fig. 4. The potentiometer at the bottom of the diagram varies the quiescent bias potential in all four quadrants simultaneously, setting the operating frequency of the overall array. The potentiometer at the left produces a differential deviation about the quiescent bias point with respect to the vertical axis, while the potentiometer at the right similarly produces a differential deviation about the quiescent bias point with respect to the horizontal axis. Thus, the operator can control the azimuth, elevation, and resonant frequency of the steerable and tunable array by adjusting three control knobs.

In actual applications, the precise voltages needed to achieve specific frequencies and beam geometries can be determined *a priori*, perhaps by testing on the antenna range using the analog circuit depicted in Fig. 4. Mission-specific digital control means can then be developed, in accordance with the block diagram in Fig. 5. Here each quadrant is driven by an analog buffer amplifier, the input to which is provided by a digital to analog converter (DAC).

A central processing unit (CPU) provides the required digital words to each input of the DAC, in accordance with instructions stored in a lookup table and held in either random access or programmable read-only memory (RAM or PROM). Should mission requirements change, only the lookup table in software need be changed to reconfigure the array completely to its new application or requirements.

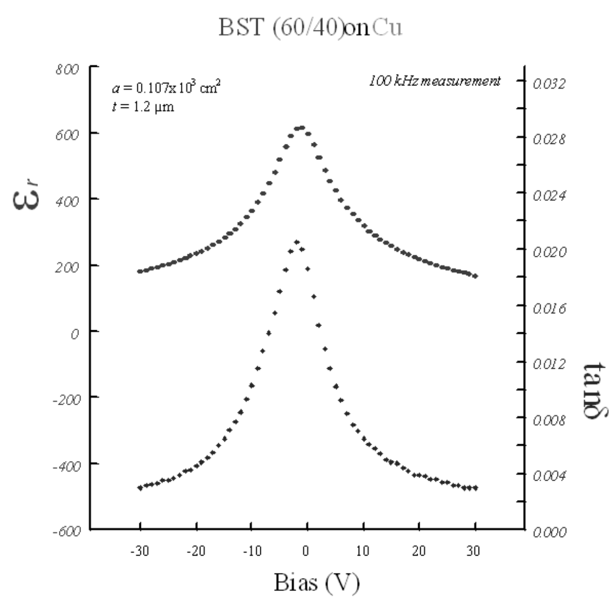

Fig. 2. C/V and Loss Tangent curves for typical ferrotunable material.

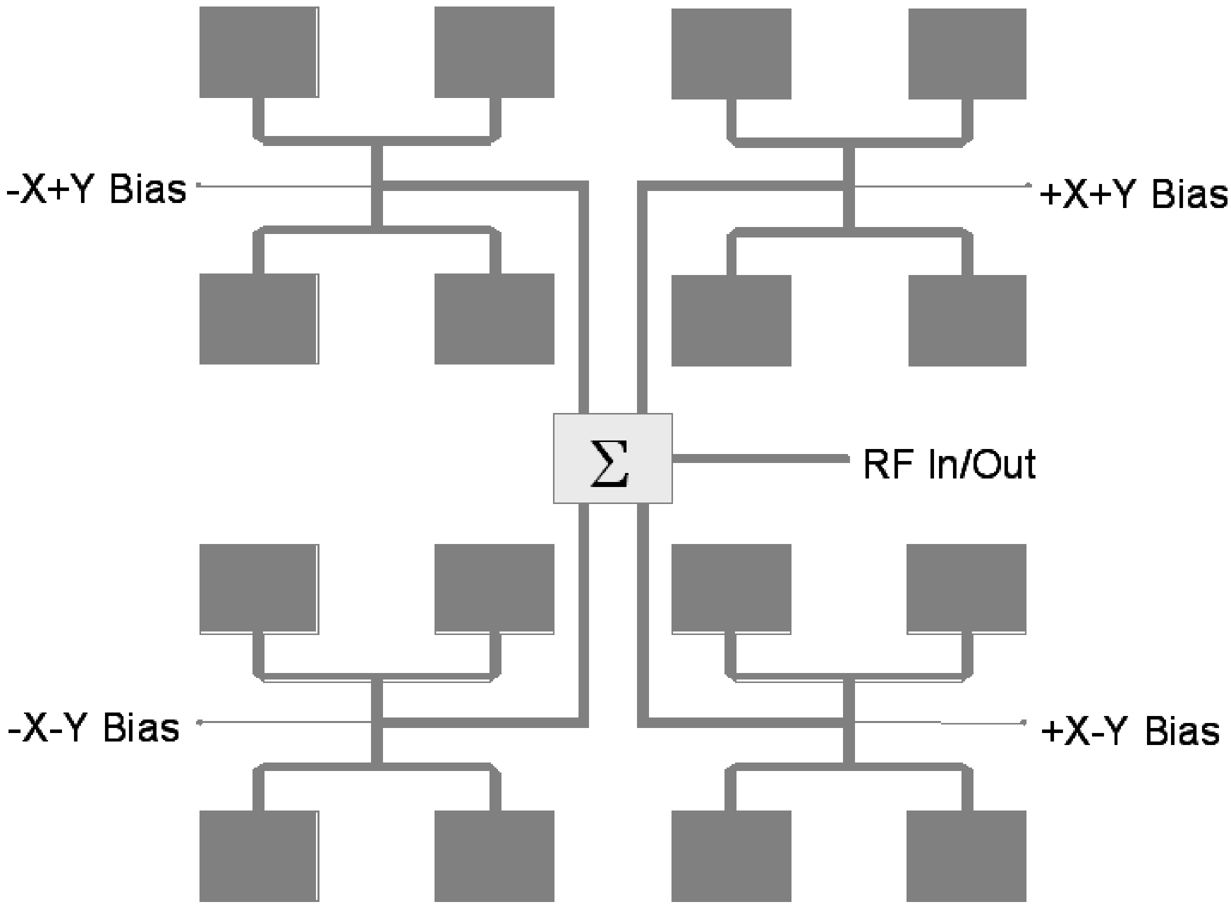

Fig. 3. Quadrant steering of microstrip patch array.

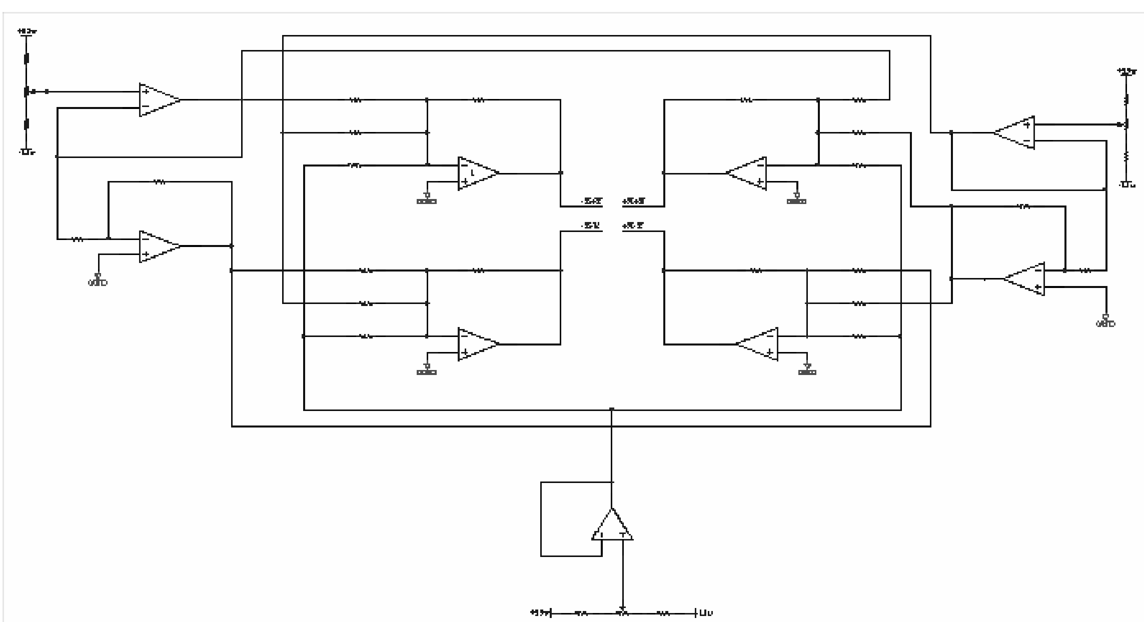

Fig. 4. General analog control electronics.

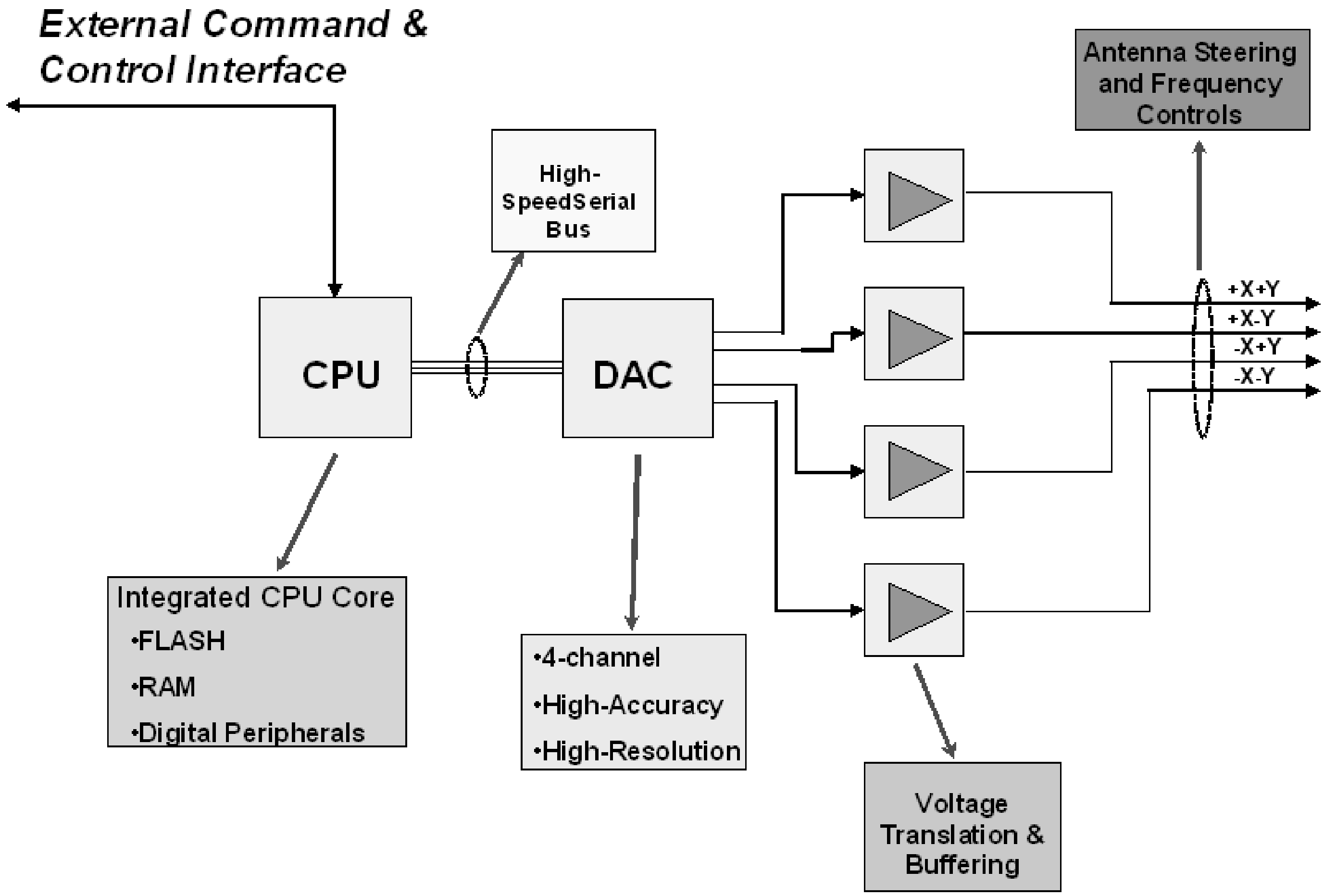

Fig. 5. Mission-specific digital control circuitry.

V. ADDING SMART STRUCTURES

Studies in the area of smart structures have resulted in the recent development of innovative materials which change shape in response to an applied electromotive force. Antennas have been previously proposed which attach a polyvinylidene fluoride (PVDF) film to a metallized mylar substrate. A voltage drop across such materials will cause them to expand or contract, reshaping their resulting curvature. The beam pattern of a parabolic antenna employing such an adaptive reflector will thus vary as a function of an applied DC potential.

Instead of restricting the use of smart structures to reshaping passive elements such as cylindrical parabolic reflectors, QorTek proposes bonding a quasi-planar but flexible, electrostatically tunable and steerable phased array antenna as described above, to an electrically reshapable backing structure. (See Fig. 6). The combination of electrostatic tuning, electrostatic steering, and mechanical shaping by means of a voltage-controlled deformable active substrate maximizes the utility of the resulting adaptive antenna assembly.

VI. TECHNOLOGY DEMONSTRATED

Now midway through a three-year technology demonstration project for the NASA Earth Science Technology Office, QorTek has developed a sixteen-patch demonstration array (see Fig. 7) 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). Driven by an analog control board (Fig. 8) based upon the concept shown in Fig. 4, this test antenna operates in S-band with a frequency tuning range of roughly 100 MHz, and demonstrates limited angular beam steering under voltage control. Upon availability of suitable materials, we anticipate migrating this design onto a ferrotunable substrate, significantly increasing both tuning range and angular beam steering capability.

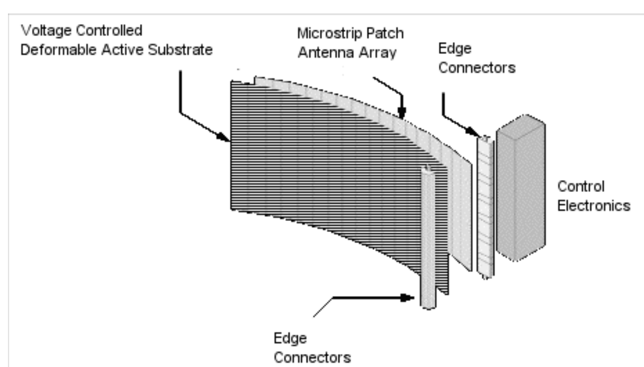

Fig. 6. Use of active substrate for antenna steering.

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 ferrotunable 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 second half of this three-year contract, QorTek plans to further optimize the basic design, and implement it more fully on new materials as they become available.

ACKNOWLEDGMENTS

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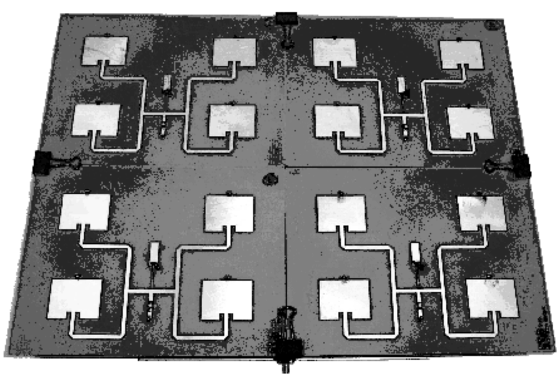

Fig. 7. Varactor-tuned test array on conventional substrate.

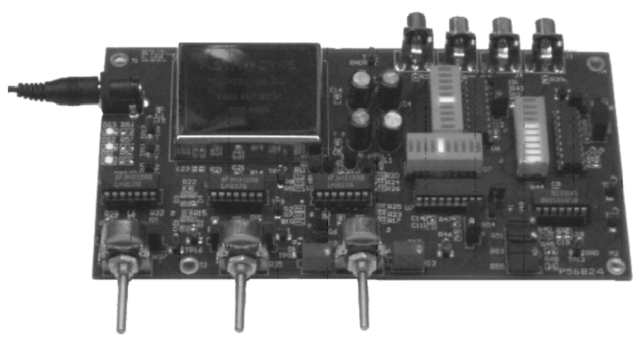

Fig. 8. Analog test fixture for limited frequency tuning and beam steering.