K-Band Phased Array Antennas Based on $Ba_{0.60}Sr_{0.40}TiO_3$ Thin-Film Phase Shifters

Robert R. Romanofsky, *Senior Member, IEEE*, Jennifer T. Bernhard, Frederick W. Van Keuls, *Member, IEEE*, Félix A. Miranda, *Senior Member, IEEE*, Gregory Washington, and Chadwick Canedy

***Abstract*—This paper summarizes the development of a prototype 23.675-GHz linear 16-element scanning phased array antenna based on thin ferroelectric film coupled microstripline phase shifters and microstrip patch radiators. A new type of scanning reflectarray antenna is introduced.**

***Index Terms*—Ferroelectric devices, phase shifters, phased array antennas, scanning antennas.**

I. Introduction

SCANNING phased array antennas are desirable for low earth orbiting communications satellites, missile seekers, automotive radar, and other remote sensing and industrial applications because of swift and vibration-free tracking capability. A prototype scanning 16-element linear phased array using $Ba_{0.60}Sr_{0.40}TiO_3$ films on 0.3-mm-thick MgO has been developed. An operating frequency of ≈23.5 GHz was chosen because it is near the allocations for NASA's Tracking and Data Relay Satellite (TDRS) H, I, J system's Ka-band forward data service and traffic radar. Anticipated effective isotropically radiated power requirements for the former may approach 39 dBW to support high-data-rate delivery (e.g., 155–622 MBPS) at wide scan angles $(>42^\circ)$ [1]. Automotive radar for intelligent cruise control or collision warning appears to require an angular resolution of 1.5–3°with about 10 mW output power to deal with a cluttered multiple-target environment [2], [3]. Frequency modulated continuous wave (FMCW) systems at 76–77 GHz are under investigation because of hardware size limitations and weather considerations, and it is an allocated band. The novel phase shifters and array concept described in this paper may be attractive for both of these applications because of their potential for better performance and lower cost. Later, a reflectarray antenna concept based on thin ferroelectric films will be introduced that can in principle provide arbitrarily high gain. Conventional manifold fed phased arrays suffer from beam-forming loss that places considerable burden on power amplifiers. The inefficiency can result in severe thermal management problems. Wide-band high-order modulation formats (e.g., quaternary phase-shift keying) require significant backoff to improve linearity and reduce bit error rate, further exacerbating the thermal problem. The potential for lower cost stems from the simple lithography inherent to the coupled-line ferroelectric phase shifter design and the anticipated economy of straightforward material growth methods like sol-gel or combustion chemical vapor deposition [17], [37]. In the case of automotive applications, a cost target of perhaps $150 per radar for the consumer market makes an elegant scanning phased array solution elusive given conventional approaches. Other methods such as mechanical scanning and overlapped multiple beams are being developed until a cost breakthrough is realized [4], [5].

Competing phase shifter technology is based on ferrites, GaAs monolithic microwave integrated circuit (MMIC), and microelectromechanical system (MEMS) designs. Ferrite phase shifter technology has been very successfully employed in military systems despite high cost and complicated current switching circuitry to generate the magnetic field. GaAs switched-line phase shifters have demonstrated good phase and amplitude error control [6]–[8]. These designs use submicrometer MESFET switches and varying microstrip line lengths or loaded lines. But the insertion loss is generally 2 dB per bit (≈36°/dB) or more at Ka-band, and thus they are not suitable for reflect array transmit or receive applications. The cost of the GaAs material and process still seems too high for consumer phased array applications. MEMS-based designs have recently demonstrated a figure of merit of 70°/dB at 40 GHz [9]. In that design, a coplanar waveguide line was capacitively loaded with MEMS bridges. The switching speed, ultimate yield, and cost of such devices remain issues ,but the MEMS technology clearly can provide high-performance alternatives for frequency and phase agile microwave electronics.

Interest in ferroelectric-based agile microwave circuits is mounting because of their high power-handling capability [10], [11], negligible dc power consumption, and potential for low loss and cost. The ferroelectrics used in this work belong to the perovskite crystal family, coined by a Russian mineralogist following the discovery of $CaTiO_3$ in 1839 after Perovsky, who reigned as minister of lands [39]. The dielectric constant of single crystal $SrTiO_3$, an incipient ferroelectric, can be depressed from about 20 000 to 2000 with a dc field of 10^4 V/cm at 4.4 K (breakdown voltage for the materials of interest here is $>10^5$ V/cm) and the loss tangent maintained below 0.001. Thin films of $SrTiO_3$, on the other hand, exhibit $\tan\delta$ as

Manuscript received March 6, 2000; revised August 23, 2000. This work was supported by the NASA Glenn Strategic Research Fund, the NASA Glenn Commercial Technology Office, and the NASA Cross Enterprise Technology Development Program.

R. R. Romanofsky and F. A. Miranda are with the National Aeronautics and Space Administration, Glenn Research Center, Cleveland, OH 44135 USA.

J. T. Bernhard is with the University of Illinois, Urbana, IL 61801 USA.

F. W. Van Keuls is with the Ohio Aerospace Institute, Cleveland, OH 44142 USA.

G. Washington is with The Ohio State University, Columbus, OH 43210 USA.

C. Canedy was with the University of Maryland, College Park, MD 20742 USA. He is now with Intel Corporation, Hillsboro, OR 97124 USA

Publisher Item Identifier S 0018-9480(00)10781-1.

poor as 0.01 with a peak relative dielectric constant of ≈5000. The dielectric constant also tends to exhibit a broad maximum with temperature as opposed to bulk material. The differences in behavior have been attributed to domain wall motion, compositional inhomogeneities, interface layers between the film and electrodes, and lattice mismatch induced stress. And $\tan\delta$ tends to increase with film thickness [14]. The Curie temperature can be tailored for a specific operating temperature by adjusting the composition of $Ba_xSr_{1-x}TiO_3$ (BST) where 0< x <1 and for room temperature $x \approx 0.60$. Devices are usually operated in the paraelectric phase slightly above the Curie temperature where hysteresis effects are small. Attempts to reduce $\tan\delta$ have included annealing and the use of dopants [15]–[18]. Tunable oscillators, filters, and antennas have been demonstrated at Ku-band and higher frequencies [12], [13], [26]. Several ferroelectric phase shifters have been developed with varying degrees of success. A strip-line circuit with a BST capacitor provided a differential phase shift of 11° at X-band with a biasing field of 70 kV/cm [19]. In that same work, a center-wire bias waveguide phase shifter produced more than 360° of phase shift at Ku-band by changing the bias between the wire and waveguide walls from 0 to 2500 V. A planar microstrip phase shifter was reported in [20] that provided 20°/kV at 2.65 GHz. A phase shift of 165° at 2.4 GHz with only 3 dB loss and a bias of 250 V was obtained from a microstrip on a thin BST slab synthesized using a sol-gel technique [21]. A 40-GHz phased array antenna that used radiating slots in waveguide and a BST film sintered onto a MgO substrate was discussed in [22]. Voltage applied across a periodic set of electrodes changed the dielectric constant of the BST from 700 to 1500, and a $\tan\delta$ of 0.05 was reported. A ferroelectric lens that uses BST slabs sandwiched between conducting plates was proposed in [23]. The approaches advanced thus far have not been able to simultaneously address low cost, low loss, and low bias voltage. In some cases, the impedance variation, due to widely changing permittivity, poses additional difficulties. We have developed phase shifters that use coupled microstriplines as dc electrodes to polarize a thin (≈1 μm) ferroelectric film. With $YBa_2Cu_3O_{7-\delta}$ electrodes and 2.0-μm-thick $SrTiO_3$ films, we obtained a figure of merit approaching our goal of 120°/dB at 40 K [24]. At room temperature using Au electrodes and 400-nm-thick $Ba_{1-x}Sr_xTiO_3$ films, some devices have demonstrated ≈70°/dB [25]. These planar phase shifters are compact, low loss, easy to fabricate, and can provide 360° of phase shift with bias voltages under 350 V. Such devices can enhance conventional (direct radiating) phased array performance or enable a new type of reflectarray antenna [26].

II. Ferroelectric Phase Shifters

The phase shifters are based on a series of coupled microstriplines of length l and separation s patterned over pulsed laser deposited $Ba_{0.60}Sr_{0.40}TiO_3$ films nominally 400 nm thick. The maximum coupled voltage occurs when the coupled sections are a quarter wavelength long (i.e., $\beta l = 90°$). Bias up to ≈350 V is applied to the sections via printed bias-tees consisting of a quarter-wave radial stub in series with a very high impedance quarter-wave microstrip. By concentrating the fields in the odd mode, the phase shift per unit length is maximized, and by using thin ferroelectric films, the effects of high loss tangent are minimized compared to microstrip patterned directly on a ferroelectric slab. Selecting the strip spacing s involves a compromise among minimizing insertion loss, simplifying lithography, and minimizing the tuning voltage. Strip widths are chosen to approximate a 50-Ω characteristic impedance. The impedance variation as a function of bias is generally below 25%, resulting in good voltage standing-wave ratio over ≈10% bandwidths. These coupled microstrip devices rival the performance of their semiconductor counterparts at Ku- and K-band frequencies. Insertion loss for room-temperature ferroelectric 360° phase shifters at K-band can be 6 dB or better [24]–[26]. A photograph of a four-section phase shifter patterned on MgO is shown in Fig. 1.

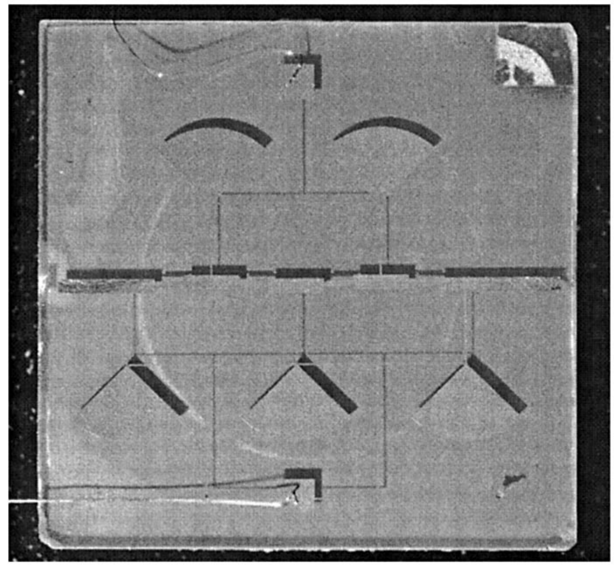

Fig. 1. Four-section $Ba_{1-x}Sr_xTiO_3$ coupled microstrip phase shifter on 0.5-mm MgO. The circuit measures 1 × 1 cm. $L = 457$ μm, $s = 10$ μm, and $w = 56$ μm.

The multilayer phase shifters have been analyzed using a computationally efficient variational method to calculate the even and odd mode capacitance [27], [28]. If a quasi-TEM type of propagation is assumed, the propagation constant and impedance can be completely determined from line capacitance. Since the cascaded coupled line circuit resembles a series of one-pole bandpass filters, as the dc bias increases, the dielectric constant of the BST film decreases, causing the passband to rise in frequency (and the $\tan\delta$ of the BST to decrease). The impedance matrix of the cascaded network can be derived by well-known coupled line theory using the superposition of even and odd mode excitation. Then an equivalent S-parameter model can be extracted and used to predict the passband characteristics of the phase shifter. Modeling and experiment has shown that the differential phase shift is roughly proportional to (film thickness)$^{0.67}$ but beyond ≈0.5 μm, the film crystal quality generally degrades. A schematic of the phase shifter cross-section is shown in Fig. 2. The bandwidth compression from tuning is evident in Fig. 3, which shows data from an eight-section phase shifter on 0.3-mm MgO using a 400-nm $Ba_{0.60}Sr_{0.40}TiO_3$ laser ablated film.

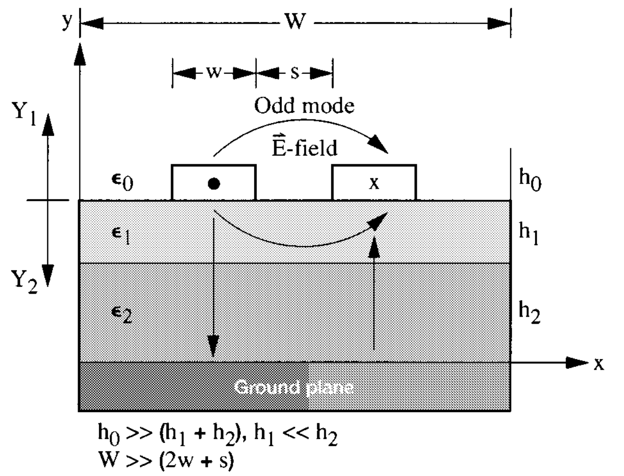

Fig. 2. Cross-section of the coupled microstripline phase shifter showing the odd-mode electric field configuration. Y_1 and Y_2 represent the admittance looking in the positive and negative y direction, respectively, from the charge plane. The thickness of the ferroelectric layer is h_1, while the host substrate has thickness h_2.

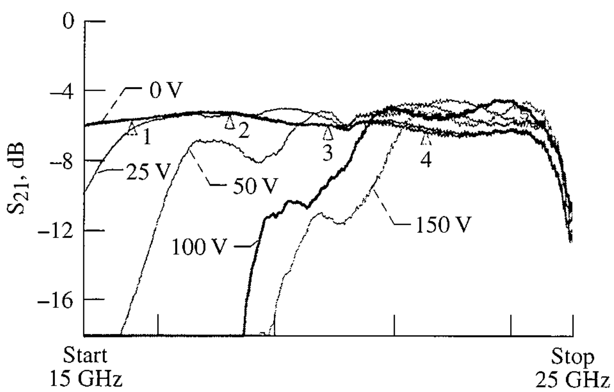

Fig. 3. Measured insertion loss (including SMA launchers) of a eight-section $\approx$50 Ω coupled microstrip phase shifter using pulse laser ablated 400-nm $Ba_{0.60}Sr_{0.40}TiO_3$ on 0.3-mm MgO as a function of bias voltage. $L = 350$ μm, $s = 7.5$ μm, and $w = 30$ μm. Markers 1, 2, 3, and 4 are at -5.75, -5.38, -6.00, and -6.49 dB, respectively.

The rolloff at the upper end of the frequency range is attributed to on-chip bias circuit effects. The bias circuits have a 25-μm-wide 1.83-mm-long high impedance line connected to a radial stub with flare angle of 75° and radius 1.17 mm.

Differential phase shift data is given in Fig. 4 for films grown by various groups. The data is for eight-section phase shifters on 0.3-mm MgO around 23.5 GHz. Variation is due to slight differences in device lengths and film uniformity.

Table I summarizes several important parameters for a *single* coupled microstrip section on $h_2 = 0.3$ mm MgO $(\varepsilon = 9.7)$ derived using the quasi-TEM analysis where ε_1 and h_1 correspond to Fig. 2. The insertion phase is designated as ϕ_I, the composite dielectric loss as α_d, and the characteristic impedance as $Z_o = [Z_{oe}Z_{oo}]^{1/2}$. In all cases, the loss tangent of the host substrate was 0.001 and the loss tangent of the ferroelectric film of thickness h_1 was taken as 0.05, 0.028, and 0.005 for ε_1 equal to 2500, 1000, and 500, respectively.

The net phase shift is 2.2 times greater for the 2-μm film compared to the 500-nm film.

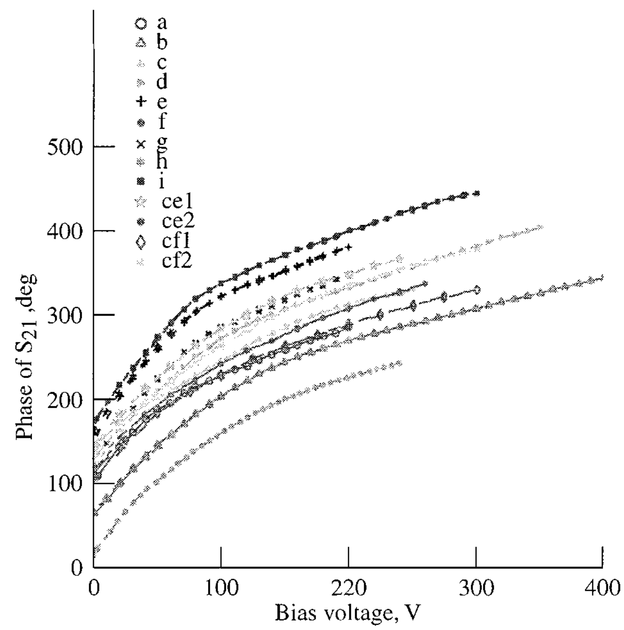

Fig. 4. Insertion phase shift for different phase shifters used in the 16-element linear array. Some phase shifters were coated with paraffin or teflon to increase the voltage breakdown strength.

III. Linear Phased Array Design

The 23.675-GHz array consists of a monolithic 1:16 microstrip beam forming manifold constructed on 0.25-mm-thick Duroid 6010, 16 ferroelectric phase shifters patterned on 1 $\times$ 0.75 cm MgO substrates, and a monolithic set of microstrip patch radiators patterned on 0.25- mm-thick Duroid 5880. Interelement spacing is 7.49 mm, which corresponds to about 0.59 free-space wavelengths. A photograph of the array is shown in Fig. 5 [29]. The original manifold, which had each successive branch of the divider networks separated by only 1.3 mm, experienced severe coupling problems resulting in considerable loss and asymmetry between ports. The distance was increased to 4 mm and resulted in a uniform insertion loss of about 13.0 $\pm$ 0.25 dB.

The patch array was originally fabricated on high dielectric constant material $(\varepsilon_r = 10.2)$. However, when the resonant frequency of each patch was measured using a HP 8510C automatic network analyzer, a large discrepancy was seen between each one. The variation was attributed to dielectric constant tolerances. Indeed, substrate tolerances are known to cause serious errors in phased array performance [30]. To circumvent the problem, a low dielectric constant homogenous material was selected. When the array was redesigned on 0.25-mm-thick Duroid 5880, the variation in resonant frequency was much smaller, about 5%, and the bandwidth was adequate. Fig. 6 depicts the measured frequency response. The patch dimensions are: $L = 4.27$ mm, $W = 6.40$ mm, and $\delta = 1.04$ mm. The gap between the feed inset and patch was 0.38 mm. No particular attention was given to reducing sidelobe levels or reducing spurious radiation from the manifold or feed.

The measured far-field radiation patterns at 0°and with an incremental 120°phase shift are shown in Fig. 7. Measured cross-polarization at boresight in given in Fig. 8. The E-plane corresponds to the elevation direction, and the H-plane corresponds to the azimuth direction. Amplitude variations, due to failures

TABLE I
THEORETICAL PROPAGATION CHARACTERISTICS OF A SINGLE COUPLED MICROSTRIP SECTION ON 0.3-mm MgO BASED ON THE QUASI-TEM METHOD DESCRIBED IN [25] AND [26]. $L = 350$, $s = 10$, AND $w = 30$ μm

ε_1	$h_1 = 2$ μm			$h_1 = 1$ μm			$h_1 = 0.5$ μm		
	ϕ_1 °	αd (Np/m)	Zo (Ω)	ϕ_1 °	αd (Np/m)	Zo (Ω)	ϕ_1 °	αd (Np/m)	Zo (Ω)
2500	65.9	66.3	29.7	50.5	45.3	37.9	40.0	30.7	46.7
1000	46.6	22.5	40.7	37.4	15.3	49.6	31.2	10.3	58.4
500	37.3	3.0	49.7	31.2	2.2	58.4	27.1	1.6	66.4

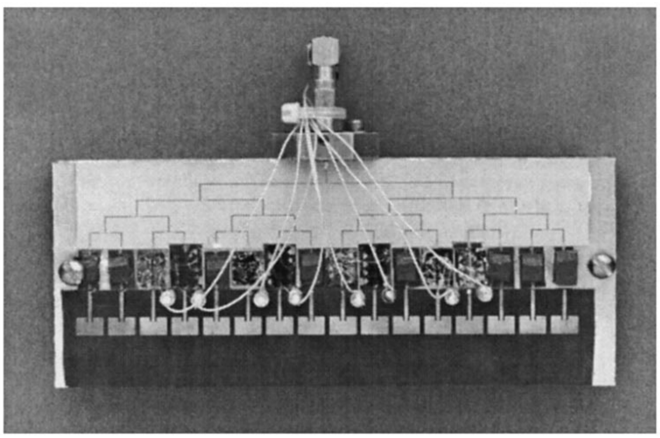

Fig. 5. A K-band 16-element linear phased array antenna using $Ba_{0.60}Sr_{0.40}TiO_3$ on 0.3-mm MgO phase shifters and microstrip rectangular patch radiators. The array is 11.9 cm long. Some of the devices are protected with a thin layer of photoresist.

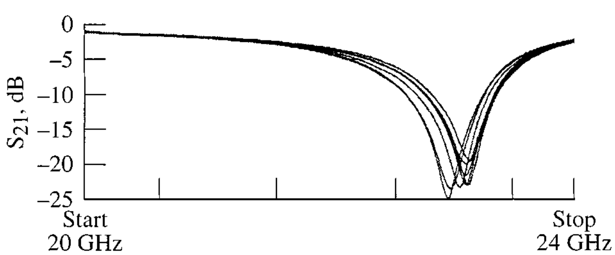

Fig. 6. Measured resonant frequency of patch radiators on 0.25-mm Duroid 5880 ($\varepsilon_r = 2.2$), 1-oz Cu clad material.

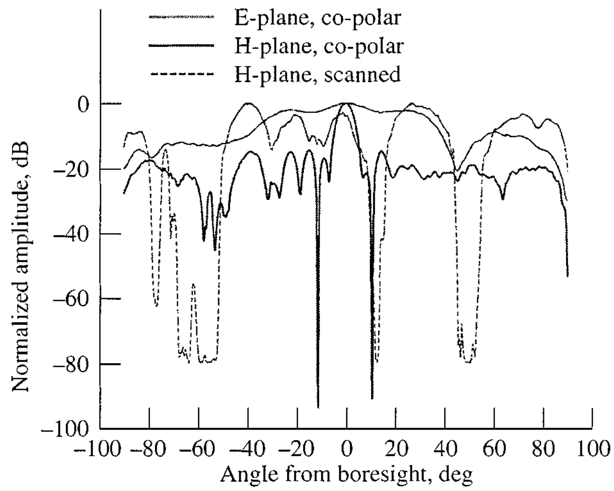

Fig. 7. Measured far-field E-plane (elevation) and H-plane (azimuth) pattern of the 16-element array at 23.675 GHz and 0 and 120° incremental phase shift.

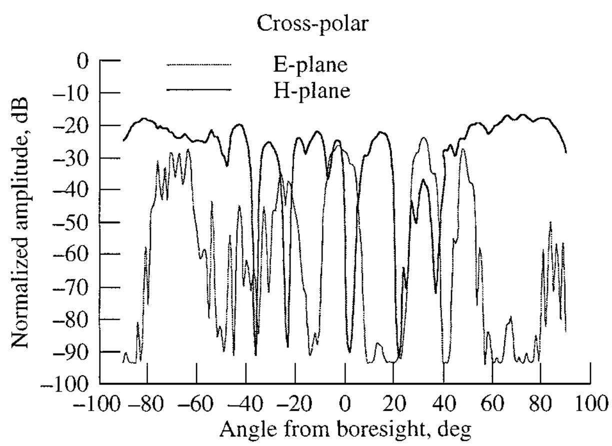

Fig. 8. Cross-polarization pattern of the 16-element at boresight.

of several phase shifters at high bias voltages that were replaced with microstrip attenuators, resulted in poorer than expected scanning performance.

However, as can be seen in Fig. 9, the phase front was coherent at the nominal 36° scan angle. The reliability and reproducibility of ferroelectric films remains the subject of dogged research. Preliminary life tests on some of our devices indicated no significant performance degradation after 10^4 voltage cycles between 0 and 350 V [31]. There may be a correlation between device robustness and doping.

An electronic module was designed and built to control the array [27]. It consists of 16 independently addressable dc-to-dc converter channels. A model AOB 16/16 analog to digital converter interfaces the controller with a PC. Since the analog-to-digital converter (A/D) could only source 5 mA per channel, an operational amplifier buffer (OPA547) was inserted between the A/D outputs and Pico Electronics model 12AV500 encapsulated dc–dc converters. A 1-W 1-MΩ resistor is strapped across the transformers output to prevent a no-load condition.

Since the dc input resistance of the phase shifters is ≫1 MΩ, the applied voltage is essentially the programmed voltage. A 0.1-μF capacitor rated at 1 KV provides some filtering. Finally, a light-emitting-diode status indictor on each channel senses whether a thermal overload condition is present. The controller board is shown in Fig. 10. It consumes about 25 mA per channel

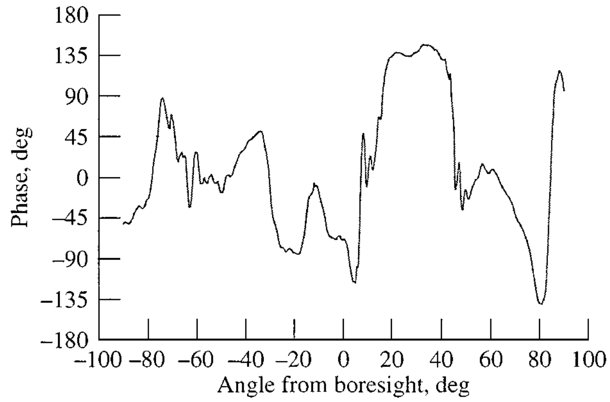

Fig. 9. Measured far-field H-plane pattern corresponding to a 120° incremental phase shift.

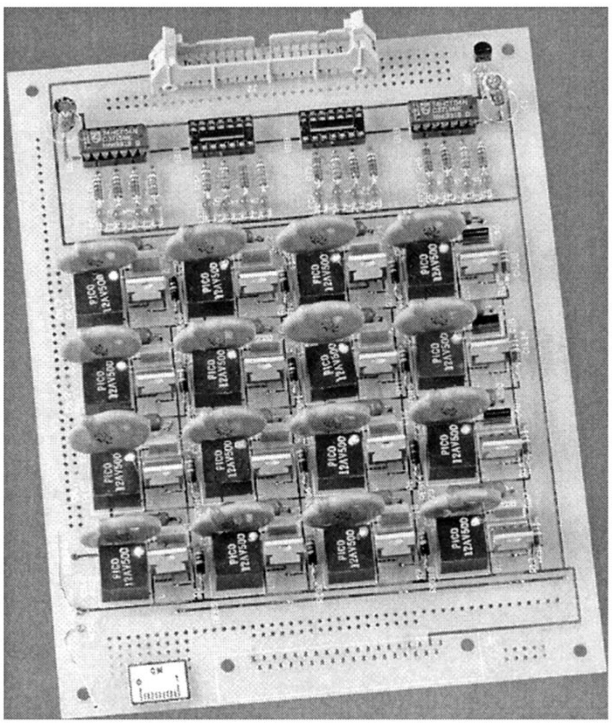

Fig. 10. High —voltage controller board for the 16-element phased array. The board measures 19 × 14.5 cm. It accepts a 0–10 V signal from a 16-channel digital-to-analog converter and outputs a linear 0–400 V control signal.

under normal conditions. An improved controller that uses a serial regulator and low-current rail-to-rail operational amplifiers is expected to reduced power consumption to less than 1 mW per channel.

IV. Ferroelectric Reflectarray

In 1963, Berry introduced a new class of antennas that utilized an array of elementary antennas as a reflecting surface [32]. The “reflectarray” has the potential to combine the best attributes of a gimbaled parabolic reflector, low cost and high efficiency, and a direct radiating phased array vibration-free beam steering. A key advantage is the elimination of a complex corporate feed network. The reflectarray consists of a two-dimensional aperture characterized by a surface impedance and a primary radiator to illuminate that surface. A microstrip reflectarray was proposed in 1978 [33]. In a microstrip reflectarray, stubs aligned

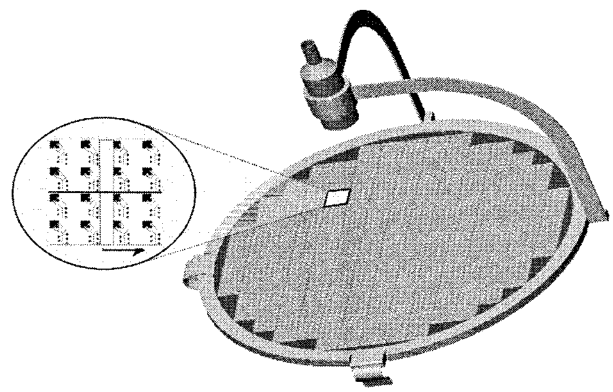

Fig. 11. A 2832-element 19-GHz ferroelectric reflectarray concept. The callout shows a 16-element subarray patterned on a 3.1 × 3.1 cm^2, 0.25-mm-thick MgO substrate. The array diameter is 48.5 cm. The unit cell area is 0.604 cm^2, and the predicted boresight gain is 39 dB.

with the desired polarization direction and of varying length are attached to the radiating elements to effect phase shift. Incident energy from the primary feed propagates down the stub, where it reflects from the open end, and reradiates with a delay corresponding to twice the electrical length of the stub. A passive 16-element microstrip reflectarray was reported in [34]. A circularly polarized microstrip reflectarray with 55% efficiency was reported in [35]. A square patch array with improved cross-polarization and high efficiency was reported in [36]. Poor cross-polarization was traced to leakage from the delay lines. To reduce the effect, the stubs were arranged in mirror symmetry instead of being collinear. Overall efficiency as high as 70% was measured. None of these were active scanning phased arrays. The ferroelectric phase shifters described in this paper can be integrated with microstrip patch radiators to form such a phase agile antenna [27], [37]. Because the antenna elements and phase shifters can be defined using a two-step lithography process, the ferroelectric reflectarray holds promise to dramatically reduce manufacturing costs of phased array antennas and alleviates thermal management problems associated with microwave integrated circuit transmit arrays. A receive reflectarray has been designed at 19 GHz and is pictured in Fig. 11. The governing design assumption is a phase shifter insertion loss of 3 dB, about 40% better than we have consistently demonstrated from $Ba_xSr_{1-x}TiO_3$ films on $LaAlO_3$ and MgO substrates. A circular aperture was approximated arranging 177 subarrays as shown to improve the aperture efficiency.

The array under development was designed to scan past a 45° angle with an interelement spacing of 0.52 wavelengths. The callout shows 16 4-section phase shifters coupled to a square patch antenna with a 90° hybrid coupler. The phase shifter is terminated abruptly in an open circuit and is used in a reflection mode. One output of the coupler has an additional 45° microstrip extension to feed the orthogonal edges of the patch 90° out of phase. For right-hand circular polarization, the phase shifter is attached to the left port of the coupler so the vertical edge of the patch receives the reflected energy with a 90° delay. While a triangular grid pattern permits the fewest elements per unit area, it was simpler to fit the phase shifters in a square unit cell. The governing assumption in the design is that a 3-dB insertion loss phase shifter can be consistently reproduced. Indeed, the phase shifter performance drives the performance and cost of the entire array. Even with a 3-dB loss device, assuming a receiver noise figure of 2 dB, the system noise temperature exceeds 800 K. Because the phase shifter is inserted between the antenna terminals and the low-noise amplifier, it has the same effect as a feed line with equivalent loss in the determination of noise. The array noise does not increase with the number of elements since the noise is noncoherent but the signal at each element is correlated [38]. Assuming an aperture efficiency of 70% and a scan loss that falls off as $\cos\theta^{1.2}$, the gain-to-noise temperature ratio (G/T) of the array is estimated at ≈3.1 dB/K. If the phase shifter loss could be reduced to 2 dB, the number of elements could be cut approximately in half.

V. Conclusion

A prototype linear K-band phased array has been demonstrated using novel coupled microstrip thin-film ferroelectric phase shifters. The phase shifters capitalize on odd mode propagation to maximize phase tuning and minimize insertion loss. Despite a fairly common misconception that ferroelectric materials have too high a loss tangent for practical microwave applications, these devices can outperform their semiconductor counterparts by several decibels. The phased array realized with these phase shifters holds promise to significantly reduce manufacturing costs of phased arrays because the phase shifters are lithographed using a simple two-step process. The finest feature size is the strip spacing, about 10 μm, compared to perhaps a 0.5-μm gate for a MESFET phase shifter at the same frequency. Batch-to-batch uniformity of epitaxial films must be improved, though, for our devices perfect crystallinity may not be optimal. This follows since higher crystal quality results in larger peak permittivity, tunability, and loss tangent. The films may ultimately be tailored to maximize the ratio of tunability to loss tangent. Coatings to increase voltage breakdown are desirable. So far paraffin and photoresist have been used with some success. To the best of our knowledge, this is the first demonstration of a K-band phased array based on ferroelectric films. A new type of scanning phased array antenna called the ferroelectric reflectarray has been introduced. The ferroelectric reflectarray holds promise to dramatically reduce manufacturing costs of scanning antennas and alleviates the thermal management problems inherent to MMIC arrays, and can provide higher gain because of quasi-optical beam forming.

Acknowledgment

The authors would like to thank N. Varaljay, B. Viergutz, and E. McQuaid for their help and expertise in processing many phase shifters. They would like to acknowledge J. Horwitz at the Naval Research Laboratory, R. Ramesh at the University of Maryland, C. Chen at the University of Houston, and J. Warner at NASA Glenn for growing the ferroelectric films used in our research over the past several years.

References

[1] J. M. Budinger *et al.*, “Direct data distribution from low earth orbit,” presented at the IEEE Int. Conf. Communications, NASA TM-107 438, Montreal, P.Q., Canada, June 8–12, 1997.

[2] P. L. Lowbridge, “Low cost millimeter wave radar systems for intelligent vehicle cruise control applications,” *Microwave J.*, pp. 20–33, Oct. 1995.

[3] D. D. Li, S. C. Luo, C. Pero, X. Wu, and R. M. Knox, “Millimeter-wave FMCW/monopulse radar front-end for automotive applications,” in *IEEE MTT-S Dig.*, June 13–19, 1999, pp. 277–280.

[4] L. H. Eriksson and S. Broden, “High performance automotive radar,” *Microwave J.*, pp. 24–38, Oct. 1996.

[5] M. E. Russell, A. Crain, A. Curran, R. A. Campbell, C. A. Drubin, and W. F. Miccioli, “Millimeter-wave radar sensor for automotive intelligent cruise control (ICC),” *IEEE Trans. Microwave Theory Tech.*, vol. 45, pp. 2444–2453, Dec. 1997.

[6] D. C. Boira and R. Marion, “A high performance 6–18 GHz five bit MMIC phase shifter,” in *Proc. GaAs IC Symp.*, 1995, pp. 267–270.

[7] D. L. Rascoe, A. L. Riley, J. Huang, V. Lubecke, and L. Duffy, “Ka-band MMIC beam steered transmiter array,” *IEEE Trans. Microwave Theory Tech.*, vol. 37, pp. 2165–2168, Dec. 1989.

[8] Z. G. Wang *et al.*, “Single-chip 4 bit 35 GHz phase shifting receiver with a Gb/s digital interface circuitry,” in *Proc. GaAs IC Symp.*, 1995, pp. 234–237.

[9] N. S. Barker and G. M. Rebeiz, “Optimization of distributed MEMS phase shifters,” in *IEEE MTT-S Dig.*, 1999, pp. 299–302.

[10] A. Kozyrev *et al.*, “Nonlinear behavior of thin film $SrTiO_3$ capacitors at microwave frequencies,” *J. Appl. Phys.*, vol. 84, pp. 3326–3332, 1998.

[11] D. Galt, T. Rivkin, and M. Cromar, “Microwave tuning quality and power handling of voltage tunable capacitors: Semiconductor varactors versus $Ba_{1-x}Sr_xTiO_3$ films,” in *Proc. Mater. Res. Soc.*, vol. 493, 1998, pp. 341–346.

[12] G. Subramanyam, F. W. VanKeuls, and F. A. Miranda, “A novel K-band tunable microstrip bandpass filter using a thin film HTS/ferroelectric/dielectric multilayer configuration,” in *IEEE MTT-S Dig.*, 1998, p. 1011.

[13] R. R. Romanofsky, F. W. VanKeuls, and F. A. Miranda, “A cryogenic GaAs PHEMT/ferroelectric Ku-band tunable oscillator,” *J. Phys. IV*, vol. 8, pp. 171–174, 1998.

[14] R. A. Chakalov *et al.*, “Fabrication and investigation of $YBa_2Cu_3O_{7-\delta}/Ba_{0.05}Sr_{0.95}TiO_3$ thin film structures for voltage tunable devices,” *Physica C*, vol. 308, pp. 279–288, 1998.

[15] G. Rupprecht and R. O. Bell, “Microwave losses in strontium titanate above the phase transition,” *Phys. Rev.*, vol. 125, no. 6, pp. 1915–1920, 1962.

[16] J. S. Horwitz *et al.*, “Structure/property relationships in ferroelectric thin films for frequency agile microwave electronics,” *Integrated Ferroelect.*, vol. 22, pp. 799–809, 1998.

[17] H. Wu and F. Barnes, “Doped $Ba_xSr_{1-x}TiO_3$ thin films for microwave device applications at room temperature,” *Integrated Ferroelect.*, vol. 22, pp. 811–825, 1998.

[18] L. A. Knauss *et al.*, “The effect of annealing on the structure and dielectric properties of $Ba_xSr_{1-x}TiO_3$ ferroelectric thin films,” *Appl. Phys. Lett.*, vol. 69, no. 1, pp. 25–27, 1996.

[19] V. K. Varadan, D. K. Ghodgaonkar, V. V. Varadan, J. F. Kelly, and P. Glikerdas, “Ceramic phase shifters for electronically steerable antenna systems,” *Microwave J.*, pp. 116–127, Jan. 1992.

[20] V. K. Varadan, K. A. Jose, V. V. Varadan, R. Hughes, and J. F. Kelly, “A novel microwave planar phase shifter,” *Microwave J.*, pp. 244–253, Apr. 1995.

[21] F. DeFlaviis, N. G. Alexopoulos, and O. M. Stafsudd, “Planar microwave integrated phase-shifter design with high purity ferroelectric material,” *IEEE Trans. Microwave Theory Tech.*, vol. 45, pp. 963–969, June 1997.

[22] O. Vendik, I. Mironenko, and L. Ter-Martirosyan, “Superconductors spur applications of ferroelectric films,” *Microwaves RF*, pp. 67–70, 1999.

[23] J. B. L. Rao, D. P. Patel, and L. C. Sengupta, “Phased array antennas based on bulk phase shifting with ferroelectrics,” *Integrated Ferroelect.*, vol. 18, 1998.

[24] F. W. VanKeuls, R. R. Romanofsky, D. Bohman, M. D. Winters, F. A. Miranda, C. H. Mueller, R. E. Treece, T. V. Rivkin, and D. Galt, “YBaCuO, Au/SrTiO/LaAlO thin film conductor/ferroelectric coupled microstripline phase shifters for phased array applications,” *Appl. Phys. Lett.*, vol. 71, no. 21, p. 3075.

[25] F. W. VanKeuls, R. R. Romanofsky, C. H. Mueller, J. D. Warner, C. L. Canedy, R. Ramesh, and F. A. Miranda, “Current status of thin film (Ba, Sr)TiO_3 tunable microwave components for communications,” presented at the 12th Int. Symp. Integrated Ferroelectrics, Aachen, Germany, Mar. 12–15, 2000.

[26] R. Romanofsky, F. W. VanKeuls, J. Warner, C. H. Mueller, S. A. Alterovitz, and A. H. Qureshi, “Analysis and optimization of thin film ferroelectric phase shifters,” in *Proc. MRS Symp.* , vol. session KK, Boston, MA, Dec. 1999.

[27] R. R. Romanofsky, “Frequency/phase agile microwave circuits on ferroelectric films,” Ph.D. dissertation, Cleveland State Univ., 1999.

[28] R. R. Romanofsky and A. H. Qureshi, “A theoretical model for thin film ferroelectric coupled microstripline phase shifters,” *IEEE Trans. Magn.*, to be published.

[29] R. R. Romanofsky, J. Bernhard, G. Washington, F. VanKeuls, F. A. Miranda, and C. L. Cannedy, "A K-band linear phased array based on BaSrTiO thin film phase shifters," in *IEEE MTT-S Dig.*, June 2000.

[30] P. Kabacik, "Design constraints of low-sidelobe microstrip phased arrays," *Microwave Opt. Technol. Lett.*, vol. 17, no. 2, pp. 107–111, Feb. 1998.

[31] F. A. Miranda, F. W. VanKeuls, R. R. Romanofsky, C. H. Mueller, and J. D. Warner, "Life cycle testing of thin film $Ba_xSr_{1-x}TiO_3$ in a tunable microwave device," presented at the Int. Symp. Integrated Ferroelectrics, Aachen, Germany, Mar. 12–15, 2000.

[32] D. G. Berry, R. G. Malech, and W. A. Kennedy, "The relectarray antenna," *IEEE Trans. Antennas Propagat.*, vol. 11, pp. 645–651, 1963.

[33] C. S. Malagasi, "Microstrip disc element reflectarray," presented at the Electron. Aerospace Syst. Conf., Sept. 1978.

[34] R. D. Javor, X.-D. Wu, and K. Chang, "Design and performance of a microstrip reflectarray antenna," *IEEE Trans. Antennas Propagat.*, vol. 43, pp. 932–939, Sept. 1995.

[35] J. Huang and R. J. Pogorzelski, "A Ka-band microstrip reflectarray with elements having variable rotation angle," *IEEE Trans. Antennas Propagat.*, vol. 46, pp. 650–656, May 1998.

[36] D.-C. Chang and M. C. Huang, "Multiple polarization microstrip reflectarray and antenna with high efficiency and low-cross polarization," *IEEE Trans. Antennas Propagat.*, vol. 43, pp. 829–834, Aug. 1995.

[37] R. R. Romanofsky and F. A. Miranda, "A high resolution scanning ferroelectric reflect array antenna," U.S. Patent 6 081 235, June 27, 2000.

[38] M. P. Delisio, R. M. Weikle, and D. B. Rutledge, "Element efficiency and noise in grid arrays," *IEEE Trans. Microwave Theory Tech.*, vol. 46, no. 11, pp. 1949–1955, 1998.

[39] V. V. Lemanov, A. V. Sotnikov, E. P. Smirnova, M. Weihnacht, and R. Kunze, "Perovskite $CaTiO_3$ as an incipient ferroelectric," *Solid State Commun.*, vol. 110, pp. 611–614, 1999.

[40] W.-Y. Lin, H. Huang, F. Yang, J. J. Schmitt, A. T. Hunt, R. R. Romanofsky, F. W. VanKeuls, F. A. Miranda, and C. H. Mueller, "Thin films of CCVD $Ba_{0.05}Sr_{0.95}TiO_3$ and $SrTiO_3$ for electrically tunable coupled microstripline phase shifters," presented at the MRS Spring Meeting, San Francisco, CA, 1999.

Robert R. Romanofsky (S'82–M'83–SM'98) received the B.S.E.E. degree from Pennsylvania State University, University Park, the M.S.E.E. degree from the University of Toledo, Toledo, OH, and the Ph.D. degree in electrical engineering from Cleveland State University, Cleveland, OH.

In 1990–1991, he was Program Manager for Superconductivity and RF Communications at NASA Headquarters, Washington, D.C. He subsequently served a three-month collateral assignment with the White House Office of Science and Technology Policy. He is currently a Member of the Applied RF Technology Branch at the NASA Glenn Research Center. He is an author or coauthor of more than 50 refereed publications in the fields of microwave device technology, high-temperature superconductivity, and microwave applications of thin ferroelectric films. He is a coauthor of a book chapter in *Low-Temperature Electronics-Physics, Devices, Circuits and Applications* (New York: Academic, 2000). He has received five patents or patents pending. His current research interests include cryogenic microwave electronics, thin-film ferroelectric technology, and phased array antennas.

Dr. Romanofsky received NASA Exceptional Service Medal.

Jennifer T. Bernhard received the B.S.E.E. degree from Cornell University, Ithaca, NY, in 1988 and the M.S. and Ph.D. degrees from Duke University, Durham, NC, in 1990 and 1994, respectively

From 1986 to 1988, she participated in Cornell's Engineering Co-op Program, working at IBM Federal Systems Division, Owego, NY. During the 1994–1995 academic year, she was a Postdoctoral Research Associate with the Departments of Radiation Oncology and Electrical Engineering, Duke University. Over the past six years, she has also worked as a Consultant on antennas and wireless communication systems. From 1995 to 1999, she was an Assistant Professor of Electrical Engineering at the University of New Hampshire (UNH), Durham. Since 1999, she has been an Assistant Professor in the Department of Electrical and Computer Engineering, University of Illinois at Urbana-Champaign. Her research interests lie in the areas of high-speed wireless data communication, reconfigurable microwave antennas and circuits, electromagnetic compatibility, and electromagnetics for industrial and medical applications.

Dr. Bernhard is a member of Tau Beta Pi, Eta Kappa Nu, and Sigma Xi. She received a National Science Foundation Graduate Fellowship, NASA-ASEE Summer Faculty Fellowships in 1999 and 2000, a NSF CAREER Award in 2000, and the 1997–1998 Teaching Excellence Award for the College of Engineering and Physical Sciences at UNH.

Frederick W. Van Keuls (M'97) received the B.S. degree *(summa cum laude)* in physics and mathematics from The Ohio State University, Cleveland, in 1985 and the M.S. and Ph.D. degrees in physics from Cornell University, Ithaca, NY, in 1987 and 1992, respectively.

His thesis work was on NMR in ^{3}He films at low temperatures. From 1993 to 1996, he investigated the electronic properties of 2D GaAs/AlGaAs heterostructures as a Research Associate at Case Western University. He joined the NASA Glenn Research Center Communications Technology division in 1996. There, his research has focused on high-temperature superconducting and thin-film ferroelectric tunable microwave components, including frequency agile filters, tunable local oscillators and phase shifters. He has coauthored more than 45 publications.

Dr. Van Keuls is a member of the American Physical Society.

Félix A. Miranda (M'91–SM'98) received the B.S. degree from the University of Puerto Rico in 1983, the M.S. degree from Rensselaer Polytechnic Institute, Troy, NY, in 1986, and the Ph.D. degree from Case Western Reserve University, Cleveland, OH, in 1991, all in physics.

He joined NASA Lewis Research Center in 1991 as a member of the Solid State Technology Branch. Since then he has been involved with experimental research on the microwave and millimeter wave properties of high-temperature superconductor (HTS) thin films, HTS-based microwave components, and thin-film ferroelectric tunable microwave components. He is an author or coauthor of more than 70 technical publications in the areas of HTS thin films, dielectrics, and tunable ferroelectric microwave components. He is a coauthor several book chapters and is the coinventor of three patent disclosures. He spent the 1998–1999 academic year as a Visiting Professor of Physics at the University of Puerto Rico, Humacao Campus. Currently, he is Chief of the Applied RF Technology Branch, Communications Technology Division, NASA Glenn Research Center, Cleveland.

Dr. Miranda is a member of the American Physical Society, the Society of Hispanic Professional Engineers, and the Forum of Industrial and Applied Physicists. In 1998 he received a NASA Administrator's Fellowship Program award.

Gregory Washington is an Associate Professor of mechanical engineering at The Ohio State University, Cleveland. He has been involved in multidomain research for the last eight years. His core area of interest lies in the area of dynamic systems: modeling and control. During this time he has been involved in the following applications: the design and control of mechanically actuated antennas, advanced control of machine tools, the design and control of hybrid electric vehicles, and structural position and vibration control with smart materials. He is presently working on ultralightweight structurally active antenna systems and other structures that involve the use of "smart materials." He is the author of more than 45 technical publications in journals, edited volumes, and conference proceedings.

Chadwick Canedy received the Ph.D. degree in physics from Brown University, Providence, RI, in 1998.

His dissertation work focused on spin-polarized transport mechanisms in magnetic multilayers and colossal magnetoresistive thin-film systems. Following graduation, he spent two years pursuing postdoctoral work in the physics department at the University of Maryland. While there, he contributed to the development and understanding of ferroelectric thin films for potential dynamic random-access memories and microwave applications. He is currently with Intel Corporation, Hillsboro, OR, working on process integration issues for next-generation microprocessors.