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Advances in Scanning Reflectarray Antennas Based on Ferroelectric Thin Film Phase Shifters for Deep Space Communications

Robert R. Romanofsky
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September 2007

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Abstract

Though there are a few examples of scanning phased array antennas that have flown successfully in space, the quest for "low-cost," high-efficiency, large aperture microwave phased arrays continues. Fixed and mobile applications that may be part of a heterogeneous exploration communication architecture will benefit from the agile (rapid) beam steering and graceful degradation afforded by phased array antennas. The reflectarray promises greater efficiency and economy compared to directly-radiating varieties. Implementing a practical scanning version has proven elusive. The ferroelectric reflectarray, under development and described herein, involves phase shifters based on coupled microstrip patterned on $Ba_xSr_{1-x}TiO_3$ films, that were laser ablated onto $LaAlO_3$ substrates. These devices outperform their semiconductor counterparts from X- through and K-band frequencies. There are special issues associated with the implementation of a scanning reflectarray antenna, especially one realized with thin film ferroelectric phase shifters. This paper will discuss these issues which include: relevance of phase shifter loss; modulo 2π effects and phase shifter transient effects on bit error rate; scattering from the ground plane; presentation of a novel hybrid ferroelectric-semiconductor phase shifter; and the effect of mild radiation exposure on phase shifter performance.

I. Introduction

Phased array antennas are an attractive alternative to gimbaled parabolic reflectors because they offer extremely rapid beam repositioning or target acquisition, spacecraft integration and packaging flexibility, and the reliability associated with "graceful degradation." Active phased arrays have been used for commercial telecommunications applications such as Iridium, and an X-band array was flown on NASA's EO-1 mission. The MESSENGER spacecraft, designed to orbit planet Mercury, represents the first deep-space telecommunication application of a phased array. Other space applications for microwave phased array antennas include any mission scenario benefiting from vibration-free or rapid (non-mechanical) beam steering. Examples could include precision interferometry involving cooperative spacecraft and especially for planetary rovers communicating to orbiting satellites to compensate for position and orientation changes experienced by the rover. Furthermore, there is speculation that futuristic Mars exploration scenarios will require data rates approaching one gigabit per second. At Ka-band frequencies, apertures approaching 10 m in diameter could be required. Such large apertures translate into very narrow beam-widths and consequently the possibility of substantial pointing errors. A reflectarray could be used as the subreflector of a Cassegrain antenna system, for example, to provide several beam-widths of beam steering. A prototype MMIC array for a similar application was demonstrated in reference 1. Other likely space applications include orbital debris radar, docking systems, and remote sensing. The utilization of phase arrays for other planetary space applications was discussed in reference 2.

The reflectarray is an alternative to directly-radiating phased array antennas and promises higher efficiency at reduced cost. A key advantage of reflectarray antennas over conventional phased arrays is elimination of the complex beam-forming manifold and costly transmit/receive modules. The reflectarray is also reciprocal—the same aperture can be used for transmit and receive functions. But a viable technique for including variable phase shift with the printed radiators to permit beam scanning has proven elusive. In 1963 Berry introduced this new class of antennas that utilized an array of elementary antennas as a reflecting surface (ref. 3). In 1975 Phelan patented a scanning reflectarray based on interleaved Archimedian spiral antennas (ref. 4). Spiral arms were interconnected with diode switches. The spirals are inherently circularly polarized over a broad bandwidth. (Far-field phase shift from a circularly polarized radiator is proportional to the apparent physical rotation of the radiator.) In 1978 Malagisi proposed a microstrip reflectarray (ref. 5). In a microstrip reflectarray, stubs aligned with the desired polarization direction and of varying length are attached to the elements to effect phase shift. Incident energy from the primary feed propagates down the stub, where it reflects from the open (or short) end, and re-radiates with a delay corresponding to twice the electrical length of the stub. A circularly polarized microstrip reflectarray with a 55% efficiency was reported by Huang and Pogorzelski (ref. 6). The antenna used square patches with identical stubs but varying rotation angles.

Tunable, reflection-mode phase shifters are required for beam-steerable reflectarrays, and replace the fixed-delay stubs in a passive array. The ferroelectric reflectarray holds promise to dramatically reduce manufacturing costs of phased arrays and alleviate thermal management problems associated with microwave integrated circuit transmit arrays. Successful technological and economic operation depends on the realization of very low loss, very low cost phase shifters.

II. Reflectarray Fundamentals

A scanning reflectarray consists of a *flat* surface with diameter D, containing MxN[1] integrated phase shifters and MxN patch radiators with inter-element separation d, that is illuminated by a single feed at a virtual focus located a distance F from the surface such that F/D ≈1 (fig. 1). This value of F/D is a reasonable compromise between feed gain (and blockage) for proper illumination and modulo 2π effects described in III.1. (The control algorithm is nearly identical to that of a conventional phased array, the exception being an a priori setting of all phase shifters to compensate for the spherical wave-front from the feed. That is, in order for the reflectarray to emulate a parabolic surface, the phase shifters are adjusted to compensate for the increasing path length from the aperture center towards the perimeter.) If the phase shifters are to be integrated onto the radiating surface they must be very small (i.e., $<\lambda_o/2$). The modulated signal from the feed passes through the reflect-mode phase shifters and is re-radiated as a focused beam in essentially any preferred direction in the hemisphere in front of the antenna, as in a conventional phased array.

Of course the physics insofar as inter-element spacing, mutual coupling, scan loss, etc. is concerned is the same as for a conventional array that uses a transmission line manifold to distribute the signal among the MxN elements.

The actual field in beam direction $\mathbf{U}_o$ consists of the desired re-radiated field from the patch elements, scattered fields from the ground plane and phase shifters, and possibly a direct field from the feed. For example, consider the E-field pattern shown in figure 2 which corresponds to a radar cross-section measurement of a 208 element passive reflectarray constructed on a 0.79 mm thick substrate with a dielectric constant of 2.2. Microstrip π radian delay lines on every other patch element were oriented such that they would be sensitive only to vertical polarization. The scattered energy from the ground plane at boresight (central red lobe) is nearly as prominent as the desired beams (red traces at ± 30°). The array reverse (ground plane only) shows the image pattern of the feed horn (blue trace). In practice, the aperture gain must be much greater than the feed gain to mitigate this effect. I.e., the image of the feed will be projected normal to the reflectarray surface because of scattering, primarily from the ground plane.

In principle, the image can be cross-polarized with respect to the desired beam. Consider the simplified schematic of a patch antenna attached to orthogonal microstrip lines feeding some type of combiner that ostensibly leads to a variable phase shifter, as shown in figure 3, where $\Delta x = \Delta y + \pi/2$[2]. The reflectarray is in the X-Y plane.

[1]The actual number of elements is truncated for a practical circular aperture of diameter D inscribed inside the rectangular aperture defined by M x N.
[2]In practice, a quadrature (90°) hybrid coupler or equivalent would be used to couple the patch to the phase shifter.

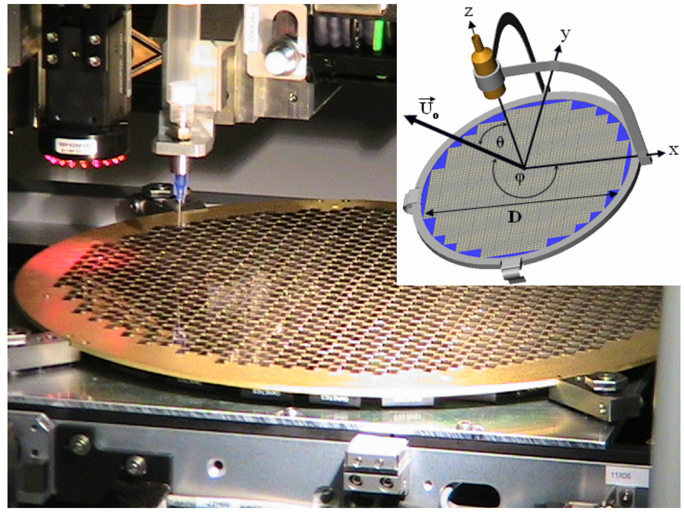

Figure 1.—19 GHz, 615 element Ferroelectric Reflectarray being populated with overlay (parasitic) patch radiators and conceptual feed attachment (inset). The array diameter is 28 cm.

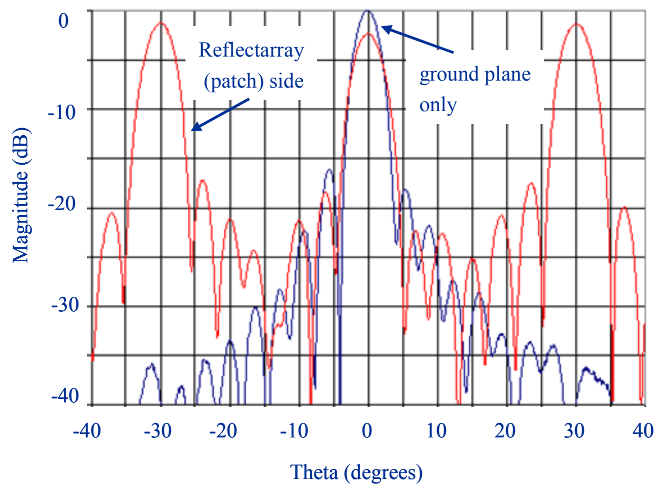

Figure 2.—Measured 19 GHz radar cross section of a 208 element passive reflectarray constructed on 0.79 mm thick substrate with ε_r=2.2.

Assume that the incident wave is in the minus z direction and right hand circularly polarized (RHCP) such that

$$E_{inc} = (ju_x - u_y)e^{j\beta z_e - j\omega t} \quad (1)$$

where u_x and u_y are unit vectors in the x- and y-directions respectively. Ignoring the time dependency, the reflected field is

$$E_{ref} = e^{2j\beta\Delta y}(-ju_x - u_y)e^{-j\beta z} \quad (2)$$

and the electric field vector angle is easily shown to be proportional to ωt so it is likewise RHCP. Phase shifter contributions are neglected. The signal reflected from the ground plane will be LHCP due to the reversal of propagation direction. It can be shown that, in general, if one arm of the patch is 90° longer than the other, the reflected signal will have the same sense polarization as the incident signal.

The most troublesome issue with implementing a scanning reflectarray arises from the fact that the phase shifters are necessarily between the feed and the patch radiating elements. Hence, they introduce line loss in front of the first stage low noise amplifier (LNA) and can cause system noise temperature to escalate in the case of a receive array. Analogously, in the case of a transmit array, the phase shifters largely determine system efficiency. However, most of the EIRP can be generated by the aperture instead of the amplifier, so there is an inherent spacecraft prime power advantage over a conventional directly radiating array. Figure 4 shows calculated EIRP and power consumption for a reflectarray and MMIC array[3]. The MMIC array used a microstrip corporate feed network, which results in an additional inefficiency because of significant dissipation in the manifold (ref. 7). We have already devised relatively low loss phase shifters based on thin ferroelectric films (refs. 8 to 10) and they will be described in section III. The next barrier to implementation is constructing the active array economically. The ferroelectric phase shifters require only one or two bias lines and can be fabricated using a simple three-step (selective etch, metallization, and encapsulation) lithography process. The smallest feature size is the 8.5 μm electrode separation ("s" in fig. 5) as opposed to submicron lithography that would be required for GaAs MMIC technology. The reflectarray structure requires only a multilayer DC bias distribution board, a support platen which also serves as the DC and RF ground plane, and the RF layer populated with MxN devices (patch antennas and phase shifters) that can be automatically placed and wire bonded (fig. 1). These qualities lead to comparatively low cost. A corrugated or dual-mode feed horn plus supporting struts, an amplifier, and a controller complete the system front end. The gradual increase in power for the reflectarray curve in figure 4 is associated with the increase in the number of controller channels. A 616 channel controller that consumed only 25 W has been built to operate the reflectarray pictured in figure 1.

We established an ambitious goal to develop a 3 dB insertion loss phase shifter at Ka-band and a 2.5 dB loss phase shifter at X-band. The remainder of this paper summarizes various phase shifter results and the overall impact of phase shifter performance on reflectarray performance.

[3]Reflectarray Assumptions: 10 W, 40% efficient TWT feed, 4 dB loss phase shifters, 41 mW per channel controller power consumption. Direct Radiating MMIC Array Assumptions: 100 mW, 15 % efficient MMIC amplifiers, 85 % efficient power supply.

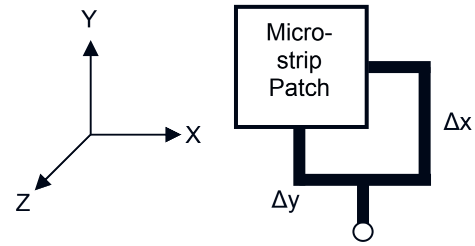

Figure 3.—Schematic of a patch antenna fed orthogonally with microstrip lines for the purpose of evaluating the polarization of the reflected field.

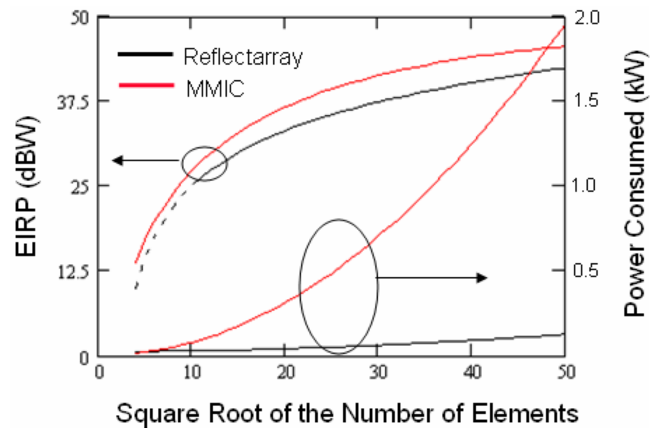

Figure 4.—Calculated EIRP and power consumption for a ferroelectric reflectarray and a direct radiating MMIC phased array as a function of the square root of the number of radiating elements.

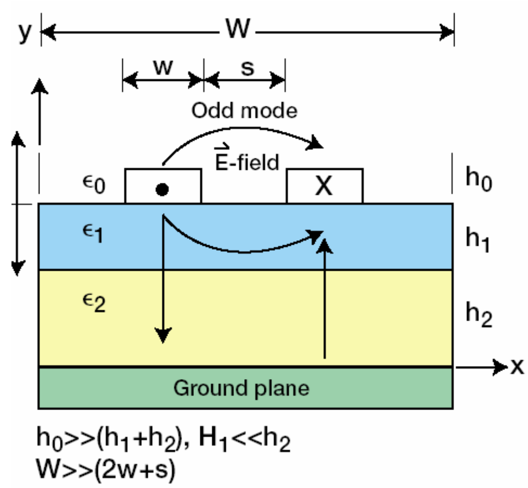

Figure 5.—Cross section of a $\lambda_g/4$ coupled microstrip line phase shifter. The coupled lines also act as the ferroelectric film biasing electrodes. The ferroelectric film (ε_1) and substrate (ε_2) thickness are h_1 and h_2, respectively.

III. Phase Shifters

Competing phase shifter technology is based on ferrites, GaAs MMIC and MEMS designs. Ferrite phase shifter technology has been very successfully employed in military systems despite relatively 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. These designs use submicron MESFET switches and varying microstrip line lengths or loaded lines. But the insertion loss is generally ≈2 dB per bit (≈45°/dB) or more at Ka-band and thus they are not suitable for all (e.g., reflectarray) applications. Furthermore the cost of the GaAs material and process, especially T/R module integration, still seems too high for non-military phased array applications. MEMS based designs have demonstrated a figure of merit of 70°/dB at 40 GHz (ref. 11). In that design a CPW line was capacitively loaded with MEMS bridges. The switching speed, reliability, ultimate yield and cost (especially packaging) of such devices remain issues but the MEMS technology clearly can provide high performance alternatives for frequency and phase agile microwave electronics (ref. 12).

Interest in ferroelectric based agile microwave circuits is mounting because of their high power handling capability, negligible DC power consumption, and potential for low loss and cost. The ferroelectrics used in this work belong to the perovskite crystal family. 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 (tanδ) maintained below 0.001. Thin films of $SrTiO_3$ on the other hand exhibit tanδ as 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. Also, tanδ tends to increase with film thickness. 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 $x\approx0.60$. Devices are usually operated in the paraelectric phase slightly above the Curie temperature where hysteresis effects are small. Attempts to reduce tanδ have included annealing and the use of dopants (refs. 13 and 14). Excellent device results have been obtained from slow wave circuits using parallel-plate ferroelectric varactors (refs. 15 and 17). The device consists of a high impedance transmission line on sapphire, periodically loaded with $Ba_xSr_{1-x}TiO_3$ capacitors spaced by distance s. Recently, ≈360° phase shifters at K- and Ka-band exhibited an average loss of about 5 and 6 dB, respectively (ref. 18). One advantage of the parallel plate approach is that conventional tuning voltages can be used (for example, ≈10 V as opposed to >100 V for coplanar structures). Another advantage is that circuits can be fabricated on convenient substrates like Si instead of exotic, high epsilon substrates like $LaAlO_3$. We have developed phase shifters that use a series of coupled microstriplines as DC electrodes to polarize a thin (≈0.4 μm) ferroelectric film. These devices are les sensitive to interfacial effects and require simpler processing. 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 (ref. 8). At room temperature using Au electrodes and 400 nm (h_1 in fig. 5) thick $Ba_{1-x}Sr_xTiO_3$ films some devices have demonstrated ≈70°/dB (refs. 9 and 10). These planar phase shifters are compact, low loss, easy to fabricate, and can provide 360° of phase shift with bias voltages under 350 V. The films are insulating so there is essentially no current draw. A theoretical model useful for predicting the propagation characteristics (insertion phase shift, dielectric loss, impedance, and bandwidth) of a coupled microstripline phase shifter was presented in (ref. 19). A sketch of the cross-section is shown in figure 5. By concentrating fields in the odd mode, phase shift per unit length is maximized and conductor loss in the ground plane is minimized. By using the ferroelectric in thin film form the effects of high loss tangent are minimized compared to microstrip patterned directly on a ferroelectric slab. The amount of phase shift can be increased by cascading coupled line sections at the expense of bandwidth.

While these devices exhibited good performance relative to their semiconductor counterparts, they fell short of our device goals. Consequently a novel hybrid phase shifter combining an analog ferroelectric section and a “digital” switch was devised. A photograph of the hybrid ferroelectric/semiconductor phase shifter is shown in figure 6.

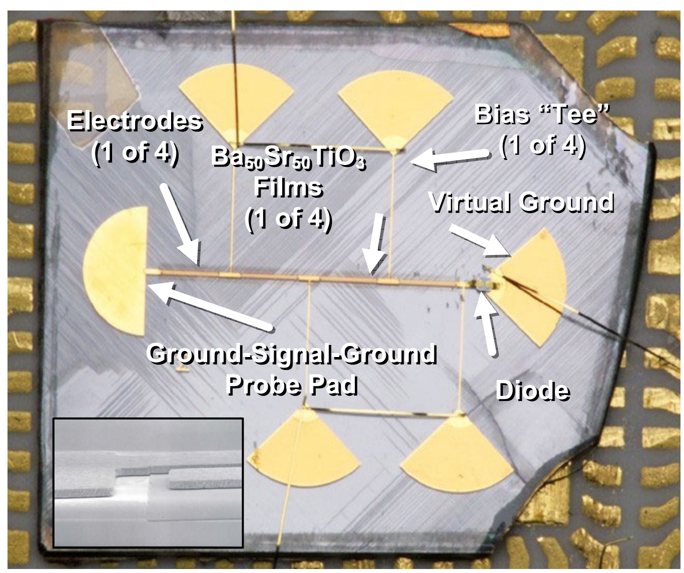

Figure 6.—Hybrid X-band ferroelectric/semiconductor phase shifter on 0.5 mm thick lanthanum aluminate. The device is 10 by 9 mm. The 1.2 mm long G-S-G pad is sacrificed (sawed) after characterization, so final size is about 9 by 9 mm^2. Each λ_g/4electrode produces ≈40° of phase shift.

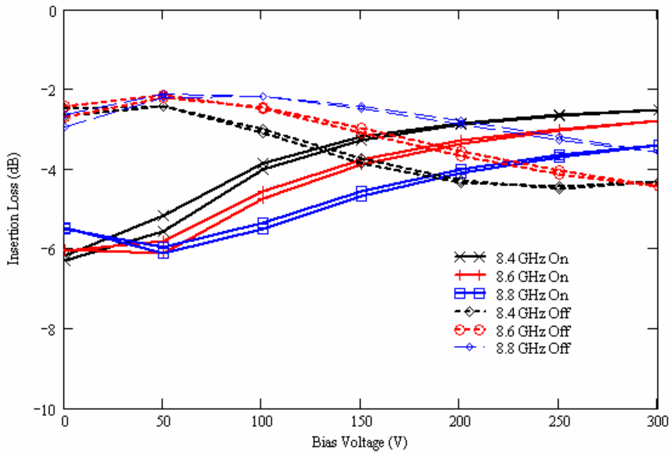

Figure 7.—Measured insertion loss of hybrid ferroelectric/ semiconductor phase shifter.

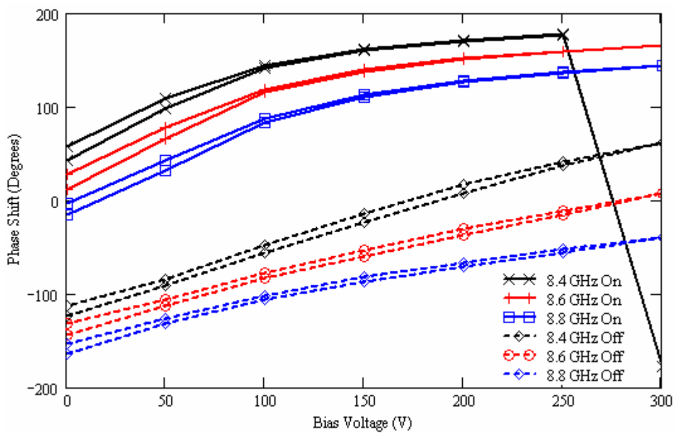

Figure 8.—Measured insertion phase of hybrid ferroelectric/ semiconductor phase shifter.

Four coupled microstrip sections are attached to a virtual short circuit (radial stub) via a GaAs beam lead diode. When the diode is forward biased, a short circuit terminates the analog phase shifters and provides an additional ~180° of phase shift. When the diode is off, the termination is essentially an open circuit with a near unity amplitude reflection coefficient and ~0° of phase shift. Measured insertion loss data are shown in figure 7. Average loss was 3.5 dB. A loss of 1.2 dB is assigned to the diode since replacing it with a true open (off) and wire bond (on) reduces the loss to 2.3 dB. Maximum phase shift was ≈320° (fig. 8).

III.1 Phase Shifter Effects on Bit Error Rate

There is an inherent intersymbol interference problem associated with the way the reflectarray operates. This phenomenon was thoroughly investigated in (ref. 20) and will be briefly reviewed here. The antenna beam is formed by superimposing reflected waves from the individual elements. These will have different delays to the observation point which are compensated by the phase shifters. But, the phase shifters are only designed to compensate for the modulo-2π phase differences. Hence the part of the delay which is an integer multiple of the carrier period is not compensated. This causes intersymbol interference (ISI) in digitally phase modulated signals. Basically, the ISI forms because the composite signal contains many component signals that can have effectively advanced or retarded phases. The effect manifests as a composite signal droop at symbol boundaries resulting in reduced Eb/No. The loss for a 26.5 GHz, 1.325 GBPS bit rate, ≈1000 element array was calculated to be 1.8 and 0.7 dB at a BER of 10^{-3} for BPSK and QPSK, respectively. This data corresponds to a θ=45°, φ=22.5° steering angle, which exacerbates the modulo 2π effect. Initially, ISI loss decreases as modulation order increases due to the decrease in the ratio of ISI length over one symbol period. This trend eventually reverses when phase distortion overcomes energy (amplitude) loss.

Phase transients during beam switching can add at least as much additional loss owing to incomplete formation of a cophasal beam during beam position updates. I.e., distortion of the beam occurs during beam evolution. Transient response must be kept much smaller than beam update rate. The measured intrinsic switching speed of the paraelectric devices reported herein is less than one nS. This should not be surprising since the dipoles must be capable of responding at the carrier frequency. Interestingly, it is the reflectarray controller that dominates switching speed. Static phase errors can also affect performance (ref. 20). Assume that the phase errors are uniformly distributed in $[-\Delta\varphi_{max}, \Delta\varphi_{max}]$. It can be shown that the averaged effect of phase error is to introduce an amplitude loss of

$$L_{\Delta\varphi} = \frac{\sin \Delta\varphi_{max}}{\Delta\varphi_{max}} \quad \text{or} \quad L_{\Delta\varphi}(\text{dB}) = \left| 20 \log \left| \frac{\sin \Delta\varphi_{max}}{\Delta\varphi_{max}} \right| \right| \qquad (3)$$

For a maximum phase error of π/8, the loss is 0.2 dB.

IV. Effect of Mild Radiation Dose on Phase Shifter Performance

One of the important applications of thin ferroelectric films is for storage elements in high-speed non-volatile memories. The effects of γ-ray total dose radiation on such ferroelectric capacitors have been investigated to evaluate vulnerability or radiation hardness. In the case of laser ablated $PbZr_xTi_{1-x}O_3$ films it was generally found that with increased total dose the dielectric constant decreased. There were also profound effects on the hysteresis curve. During irradiation, electron-hole pairs generated in the film are separated by the strong local electric field at grain boundaries. Electrons are quickly swept away but the holes are more easily captured by defects. The greater the dose the more charge is trapped. These trapped charges screen the depolarization field thereby reducing the polarization ($\mu C/cm^2$) and dielectric constant as observed by experiment.

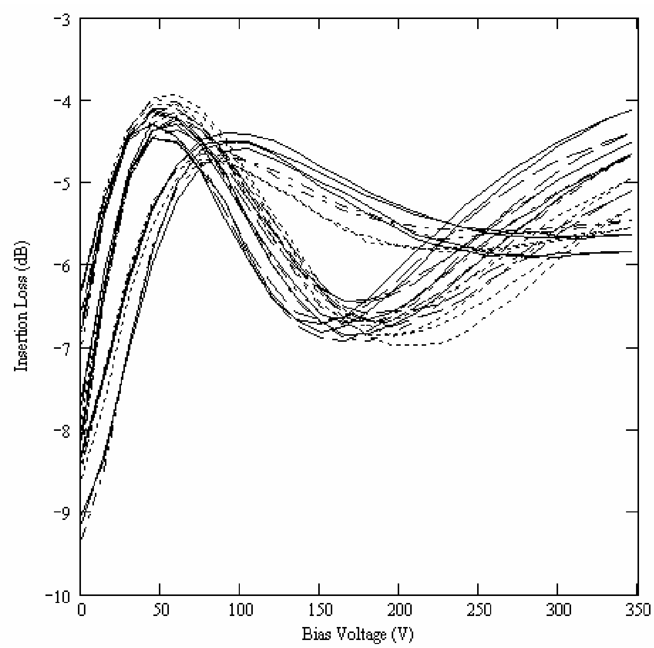

Figure 9.—Insertion loss of 13 pristine devices evaluated at ≈19 GHz. Average loss at 0 Field = 8.46 dB.

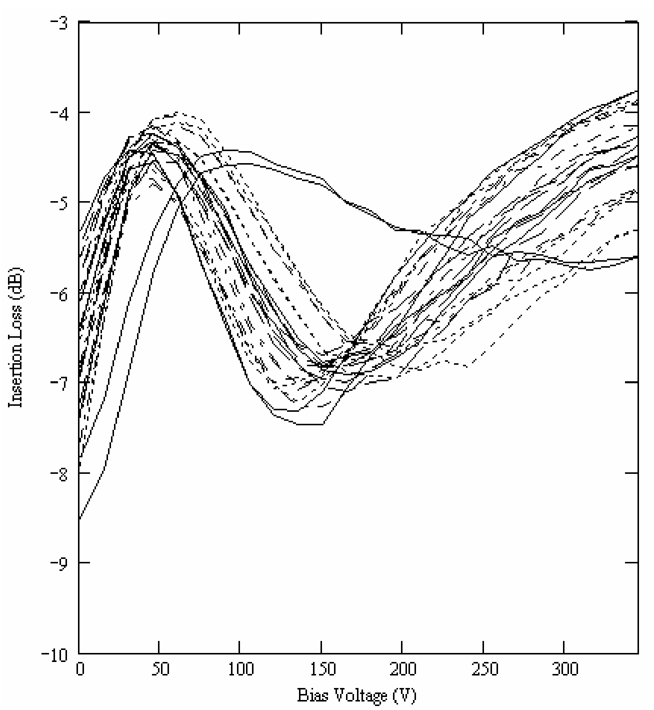

Figure 10.—Insertion loss of the same devices as in figure 8 but after exposure to 197 MeV protons with a total fluence = $9.9486 \times 10^9/cm^2$. Average loss at 0 Field = 7.47 dB

The effect of radiation on thin $Ba_{0.50}Sr_{0.50}TiO_3$ films for analog (microwave) applications has not been thoroughly evaluated. As a prelude to space qualification, coupled microstrip phase shifters were subjected to mild total dose (proton) radiation exposure using a 200 MeV beam energy with a total dose up to 600 Rad (Si) (ref. 21). The insertion loss of a set of laser ablated $Ba_{0.50}Sr_{0.50}TiO_3/LaAlO_3$ based phase shifters before and after exposure is shown is figures 9 and 10. The most salient result is that the insertion loss at 0 DC field appears to have improved by about 1 dB after irradiation. The average insertion loss at all bias fields was essentially unchanged and the change in insertion phase was unremarkable. It is known that for these highly oriented films there is a strong correlation between high dielectric constant and high loss tangent. It is possible that some minimal radiation damage affects the way in which the electromagnetic energy is coupled into acoustical (loss) modes, thereby reducing $\tan\delta$ without appreciably affecting the real part of the permittivity. Or perhaps the films are an inhomogeneous mixture of nano-scale paraelectric and ferroelectric phases and the alleged ferroelectric nano-domains tend to be pinned by additional defects caused by the radiation.

V. Conclusions

Reflectarray antennas promise substantial performance and cost advantages compared to directly-radiating phase arrays. Feed energy scattering from the ground plane compromises efficiency but is a surmountable problem. Compact and very low loss (≤ 3 dB) phase shifters, with fast transient response, are required to enable efficient and low-cost scanning reflectarray antennas. We have demonstrated very high quality microwave phase shifters employing thin, laser ablated $Ba_{50}Sr_{50}TiO_3$ films on $LaAlO_3$. A hybrid ferroelectric-semiconductor approach using a switch to toggle between antipodal phase states based on a virtual short may offer a very good solution to 3 dB loss phase shifters above X-band. Replacing the GaAs diode by an FET with the gate-to-source capacitance resonated out could improve loss by nearly 1 dB. Bit error rate degradation occurs from intersymbol interference owing to the inherent modulo-2π effect as well as finite phase shifter transient response. Low dose radiation exposure had no remarkable effect on phase shifter performance in terms of average insertion loss but may have improved zero-field loss tangent.

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14. ABSTRACT
Though there are a few examples of scanning phased array antennas that have flown successfully in space, the quest for low-cost, high-efficiency, large aperture microwave phased arrays continues. Fixed and mobile applications that may be part of a heterogeneous exploration communication architecture will benefit from the agile (rapid) beam steering and graceful degradation afforded by phased array antennas. The reflectarray promises greater efficiency and economy compared to directly-radiating varieties. Implementing a practical scanning version has proven elusive. The ferroelectric reflectarray, under development and described herein, involves phase shifters based on coupled microstrip patterned on $Ba_xSr_{1-x}TiO_3$ films, that were laser ablated onto $LaAlO_3$ substrates. These devices outperform their semiconductor counterparts from X- through and K-band frequencies. There are special issues associated with the implementation of a scanning reflectarray antenna, especially one realized with thin film ferroelectric phase shifters. This paper will discuss these issues which include: relevance of phase shifter loss; modulo 2π effects and phase shifter transient effects on bit error rate; scattering from the ground plane; presentation of a novel hybrid ferroelectric-semiconductor phase shifter; and the effect of mild radiation exposure on phase shifter performance.

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