#### LOW-COST PHASED ARRAYS USING BULK PHASE SHIFTING

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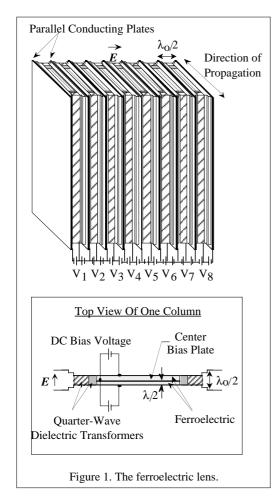
ABSTRACT – This paper presents two phased-array antenna configurations that use bulk phase shifting for realizing low-cost phased arrays. Both are lens configurations. The first configuration is based on the ferroelectric lens, which uses ferroelectric material. Ferroelectrics posses voltage-tunable dielectric constants, which can be used to generate variable phase shift. The other approach is based on the Radant lens that provides a medium that is loaded with diodes and provides the needed phase shift by switching the diodes on and off. These lenses do not contain an individual phase shifter at each radiating element rather they use row-column steering which reduces the phased array cost. After describing the two lenses, we will show how they can be used as low-cost phased arrays. A small ferroelectric lens and a  $4' \times 8'$  Radant lens have been built and tested at X band. We will present experimental results demonstrating electronic beam scanning.

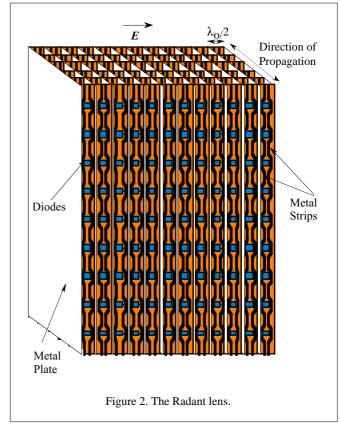
#### 1.0 INTRODUCTION

One of the most versatile antennas used in radars is the phased array. A phased array antenna can rapidly scan its beam without mechanical movement. Each radiating element of a phased array is normally associated with a phase shifter or a T/R module with which the element phase can be varied through 360° to form a beam at the desired angle. The phase shifters or T/R modules with their control circuitry along with the feed network account for the major hardware cost in the phased-array antenna. This paper examines two antenna configurations that uniquely incorporate bulk phase shifting. This reduces the number of phase shifters from  $(n \times m)$  to (n + m), where n is the number of columns and m is the number of rows in a phased array. The number of phase shifter drivers and phase shifter controls is also reduced by the same factor using row-column phase control. This reduces the cost of the phased array. The first configuration is based on the ferroelectric lens, which uses ferroelectric material. Ferroelectrics posses voltage-tunable dielectric constants, which can be used to generate variable phase shift with a dc bias voltage. The other configuration uses the Radant lens, which provides an artificial dielectric medium that is loaded with diodes; switching the diodes on and off controls the phase shift through the medium. In this paper, we will review the ferroelectric and Radant lens concepts. We will describe how these two lenses can be used as low-cost phased arrays. A small ferroelectric lens has been built and tested in an interferometer configuration at X band. A 4' × 8' Radant lens has also been built and tested at X band. Test results of both lenses demonstrating electronic scanning will be presented.

## 2.0 DESCRIPTION OF THE FERROELECTRIC LENS

The ferroelectric lens concept has been published elsewhere [1]. In this section, we briefly review the concept. The ferroelectric lens is shown conceptually in Fig. 1; each column of the lens is a pair of conducting parallel plates that are loaded with two pieces of bulk ferroelectric ceramic with a center conducting plate that is used to apply the dc bias voltage. The separation between the conducting plates is slightly less than  $\lambda_o/(1+\sin\phi_s)$ , where  $\lambda_o$  is the free space wavelength, and  $\phi_s$  is the maximum scan angle; this separation is the maximum allowed to avoid grating lobes. To propagate only the dominant transverse electromagnetic (TEM) mode and cut-off higher order modes in the ferroelectric-loaded section, the separation between the center bias plate and either conducting plate is chosen to be less than  $\lambda/2$ , where  $\lambda$  is the wavelength in the ferroelectric. Quarter-wave dielectric transformers are used to match the empty parallel-plate waveguide to the ferroelectric-loaded parallel-plate waveguide. Since the dielectric constant  $(\varepsilon_r)$  of the ferroelectric is a function of the bias voltage, by applying a different bias voltage  $(V_1, V_2, V_3)$  to each column, a linear phase gradient can be created in the E-plane. Therefore, if a plane wave is incident on one side of the lens with the electric field E normal to the plates, the beam on the other side can be scanned in the E-plane.

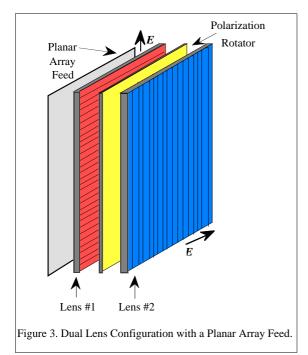


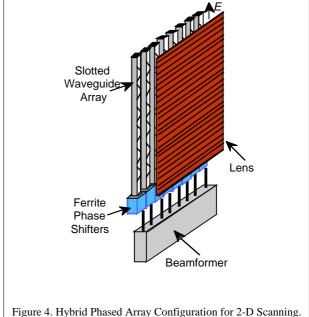


Strictly speaking, the material that we use is not a true ferroelectric. We use a bulk composite material. It is a mix of Barium Strontium Titanate (BST) in the paraelectric phase and an oxide. The oxide is added to reduce  $\varepsilon_r$  and loss tangent (tan  $\delta$ ) of the BST. However, the tunability of a composite is not as large as that of a pure BST; tunability is the fractional change in  $\varepsilon_r$  with dc bias voltage. In general, the composites with larger  $\varepsilon_r$  offer higher tunability; both large  $\varepsilon_r$  and high tunability are desired to reduce the lens size. However, the lens impedance matching is easier with smaller  $\varepsilon_r$ . Therefore, a compromise is needed between reducing the overall lens size and achieving reasonable impedance match. The composites that we used offered a good compromise among  $\varepsilon_r$ , tan  $\delta$  and tunability. Specifically,  $\varepsilon_r$  and tan  $\delta$  of these composites are 81 and 0.0069, respectively at 10 GHz. Tunability is a respectable 24% for a bias of 8 V/ $\mu$ m. Paratek Microwave, Inc. is the manufacturer of these composites, which are produced using usual low-cost ceramic processing techniques. One can show that in order to obtain 360° differential phase shift at 10 GHz, the length of the composite needed is less than 3 cm and the dielectric loss through the composite is less than 2 dB.

# 3.0 DESCRIPTION OF THE RADANT LENS

Similar to the ferroelectric lens, the Radant lens is also a novel antenna [2]. The Radant lens concept is illustrated in Fig. 2. Like the ferroelectric lens, the Radant lens is also constructed from a set of parallel conducting plates. In between each set of plates is a series of dielectric support layers on which are two strips of metal cross connected by a set of diodes. The amount of metallization controls the amount of phase shift per dielectric layer. The operating principle of the Radant lens is that the phase shift through the lens changes when the diodes in one layer are turned on or off. The Radant lens consists of several layers with each layer providing a specific amount of phase shift. The total phase shift results from selectively switching the diodes on and off on each layer using a digital bias control circuit. The simplest configuration is an *E*-plane scanning lens in which beam scanning results from a linear phase gradient along the *E*-plane dimension.





### 4.0 PHASED-ARRAY CONFIGURATIONS USING FERROELECTRIC AND RADANT LENS FOR 2-D SCANNING

A single ferroelectric or Radant lens provides one-dimensional (1-D) electronic beam scanning. Two-dimensional (2-D) beam scanning can be achieved by cascading two lenses or using one lens in a hybrid configuration with a phased array that can scan the beam in only one plane [1,2].

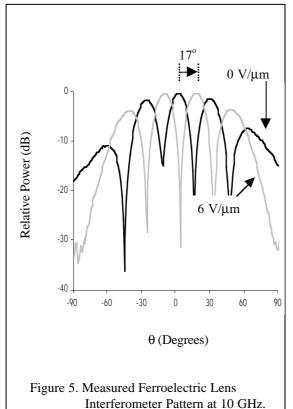
Figure 3 shows the cascading of two spatially orthogonal lenses. The first lens provides an elevation scan of a vertically polarized wave. A passive 90° polarization rotator then rotates the electric field to become horizontally polarized. The second lens then provides the azimuth scanning of the horizontally polarized wave. In Fig. 3, a non-scanning planar array is shown as the illuminator (or feed) for the dual lenses; a space feed can also be used [1]. In this configuration, in addition to scanning the beam, row-column phase controls can also be used to correct the spherical phase errors due to the point space feed; however, this phase correction is not exact, but it is satisfactory for many applications.

Another method of achieving 2-D beam scanning uses a hybrid phased array configuration. For example, a slotted waveguide array with phase shifters provides electronic beam scanning in one plane. Scanning in the orthogonal plane is obtained by placing either a ferroelectric or a Radant lens in front of the slotted waveguide array, as shown in Fig. 4.

#### 5.0 EXPERIMENTAL RESULTS

## 5.1 Ferroelectric Lens

First, we built and tested a single column of the ferroelectric lens [1]. The experimental results agreed well with the theoretical results of the lens aperture matching. Control of the column phase shift with dc bias voltage was also demonstrated. The measured loss was about 2 dB, which also agreed well with theoretical result. We would like to reduce this loss. We are pursuing material improvements as participants in the United States Defense Advanced Research Projects Agency's (DARPA's) Frequency Agile Materials for Electronics (FAME) program. We have also built and tested a two-column interferometer at X band. Both columns were 12.7 cm high, and they were spaced a distance  $2\lambda_0$ . We measured the pattern as dc bias was applied to one column to scan the phased-array antenna pattern. In Fig. 5, two of these patterns are plotted for 10 GHz frequency; the solid pattern is for the case when there is no dc bias applied; the dashed pattern is for the case when a 6  $V/\mu m$  bias was applied to one column. At 6  $V/\mu m$ , 200° differential phase shift is expected, which should scan the pattern to  $\sin^{-1}[\Delta\phi/(2\pi d/\lambda_0)] = 17^{\circ}$  as demonstrated;  $\Delta\phi$  is the phase shift, and d is the spacing between the columns. There is no indication of any material inhomogeneity in the patterns. Additional results will be presented at the symposium.



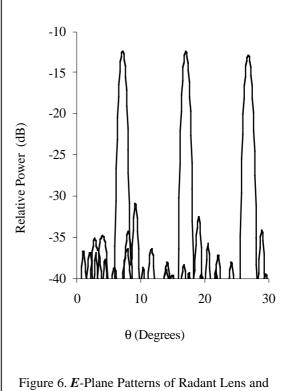


Figure 6. *E*-Plane Patterns of Radant Lens and Slotted Waveguide Array Combination Scanned to 3 Different Angles at 9.5 GHz.

## 5.2 Radant Lens

Recently, a 4' × 8' Radant lens was procured from Radant Technologies, Inc. and placed in front of a slotted waveguide phased array (modified AN/TPQ-36 antenna) [3] to form a hybrid phased array antenna. The slotted waveguide array with associated phase shifters at each column is used to scan the beam in the azimuth plane, and the Radant lens is used to scan the beam in the elevation plane. Experiments were performed at the Naval Research Laboratory's compact range on this hybrid phased array to measure insertion loss, scan loss, and pattern distortion associated with scan. Although the measured 1.5-2.5 dB loss through the Radant lens is a bit higher then the theoretically predicted loss of about 1 dB, the Radant lens performed well with good scanning properties and low radiation pattern distortion as shown in Fig. 6. The excess loss was attributable to fabrication and the type of diode used. Radant Technologies' recent experience with other programs indicates that the lens loss will be only about 1 dB. Additional results will be presented at the symposium. Radant Technologies, Inc. is planning to investigate the use of MEMS switches in place of the p-i-n diodes to reduce the loss, weight and power consumption.

### 6.0 SUMMARY

The work done so far in developing low-cost phased-array antennas at X band using the ferroelectric and the Radant lens was reviewed. A  $4' \times 8'$  Radant lens has been built and tested demonstrating electronic beam scanning. Electronic beam scanning has also been demonstrated in a two-column interferometer of the ferroelectric lens. Work is continuing in building and demonstrating a small ferroelectric lens.

#### 7.0 REFERENCES

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- 3. J. B. L. Rao *et al.*, "Affordable phased array for ship self-defense engagement radar," in Proc. 1996 IEEE National Radar Conf., pp. 32-37.