INTRODUCTION

Ferroelectric materials have the unique property of variable dielectric constant with applied DC bias voltage. This property can, in principle, be used to develop phase shifters for phased arrays. However, the high dielectric constant and the high loss of pure ferroelectric materials have limited their applications in phased arrays. Recent improvements in ferroelectric composite materials prompted renewed interest in developing phase shifters at microwave frequencies.

A typical phased array uses several thousand radiating elements and phase shifters, and hence it is very expensive. The Naval Research Laboratory (NRL) is developing a lens antenna that incorporates bulk phase shifting using ferroelectric material. The ferroelectrics were developed at the Army Research Laboratory (ARL); they are low-cost, bulk oxide-ceramic composites of Barium Strontium Titanate Oxide (BSTO). The lens approach will reduce the number of phase shifters, phase shifter drivers and controls resulting in a low-cost phased array. This paper briefly describes the ferroelectric lens concept and methods of using this lens in developing low-cost phased arrays. The properties of ferroelectric materials and the recent improvements at ARL in reducing the dielectric constant and the loss tangent are then discussed. This is followed by presentation of theoretical and experimental results and conclusions.

FERROELECTRIC LENS CONCEPT

The NRL ferroelectric lens concept has been published previously [1,2]. In this section, we briefly describe the concept. The lens is shown in Fig. 1; each column of the lens is a set of conducting parallel plates that are loaded with ferroelectric material. The material is bifurcated by a center conducting plate that is used to apply the DC bias voltage to the ferroelectric. The separation between the parallel plates at the input and output end is λ/2, where λ is the free space wavelength. Since only the TEM mode is desired, the separation between the parallel conducting plates is reduced to avoid higher order mode propagation in the dielectric loaded section of the waveguide. Specifically, the separation between the center bias plate and either conducting plate is less than λ/2, where λ is the wavelength in the ferroelectric. Quarter-wave dielectric impedance transformers are used to match the empty waveguide to the ferroelectric loaded waveguide.

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Since the dielectric constant of the ferroelectric is a function of the bias voltage, by applying a different bias voltage to each column, a linear phase gradient can be created across the lens. So, 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. A single ferroelectric lens offers only one dimensional scanning. Scanning in two dimensions can be achieved [2] by using two lenses with a polarization rotator between them. The lenses can be fed by a horn or a nonscanning planar array. Perhaps the simplest and most affordable option may be to use a slotted waveguide array with phase shifters to scan in one plane and to feed a ferroelectric lens that scans in the orthogonal plane.

FERROELECTRIC MATERIAL

A ferroelectric material possesses spontaneous polarization. However, in our application, we use the material in the nonferroelectric (paraelectric) state above the Curie temperature.

ARL has developed novel oxide-ceramic composites of BSTO along with a simple, low-cost processing technique for their manufacturing [3,4]. It involves mixing Barium Titanate (BaTiO$_3$) and Strontium Titanate (SrTiO$_3$) powders. The resulting BSTO powder is calcined and mixed with an oxide. After pressing and sintering, the composite is ready to be machined. Table 1 lists the properties of several ARL ferroelectrics at room temperature. The first column indicates the Ba/Sr ratio of the composition. The second column shows the weight % oxide in the composition. The third column is the Curie temperature. The fourth column is the ferroelectric tunability at 2 V/µm; tunability is the fractional change in the dielectric constant with applied DC bias voltage. The lower the Curie temperature, the more paraelectric (and so the less tunable) the material becomes at room
temperature. The last two columns list the dielectric constant ($\varepsilon_r$) and the loss tangent (tan $\delta$) at 1 kHz and 10 GHz. Low frequency results were calculated from capacitance measurements. X-band measurements were performed by Dr. R. Geyer at the National Institute of Standards and Technology and confirmed with NRL measurements. We see that in general, tunability, $\varepsilon_r$, and tan $\delta$ decrease with decreasing Ba content; they also decrease with increasing oxide content. After oxide is added, $\varepsilon_r$ changes much less with frequency. As expected for ceramics, tan $\delta$ increases with frequency; however, it is far lower than that of any other tunable ferroelectrics. Measurements at higher bias voltages indicate that tunability increases linearly with an increase in bias voltage.

### THEORETICAL AND EXPERIMENTAL RESULTS

For phased array applications, the amount of phase change (differential phase) needed is 360°. To obtain 360° phase shift, it can be shown that the loss the RF wave suffers as it propagates through the ferroelectric material is a function of tan $\delta$ and tunability of the ferroelectric. Loss is independent of $\varepsilon_r$. In general though, the larger the dielectric constant of the ferroelectric, the larger its tunability, the larger the loss tangent and of course, the more difficult the impedance matching problem. The $Ba_{55}Sr_{49}TiO_3$ material with 60% oxide offers a good compromise among $\varepsilon_r$, tan $\delta$, and tunability. This material can provide up to 30% tunability with high DC bias voltage; then the length needed for 360° differential phase shift is only about $\lambda_0/2$ (< 1” at 10 GHz) and the loss is ~ 2 dB at 10 GHz. Presently, ARL is investigating techniques for reducing tan $\delta$.

Theoretical analysis has been performed on one column of the lens using computer software developed at NRL based on analytical and numerical techniques. One 5” (~ 4$\lambda_0$ at 10 GHz) column has been designed and tested. Figure 2 shows the measured phase shift of the parallel plate column. Although high DC bias voltages are needed to obtain 360° phase shift, the amount of current required is small, and so the bias control power requirements are very small (~1 W).

<table>
<thead>
<tr>
<th>Material</th>
<th>Oxide (wt %)</th>
<th>Curie Temp. (°C)</th>
<th>Tunability (%)</th>
<th>$\varepsilon_r$ 1kHz/10GHz</th>
<th>tan $\delta \times 10^3$ 1kHz/10GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Ba_{55}Sr_{49}TiO_3$</td>
<td>0</td>
<td>-25°C</td>
<td>25.5</td>
<td>1908/1099</td>
<td>20.0/18.9</td>
</tr>
<tr>
<td>$Ba_{55}Sr_{49}TiO_3$</td>
<td>20</td>
<td>-55°C</td>
<td>6.44</td>
<td>592/616</td>
<td>0.73/8.7</td>
</tr>
<tr>
<td>$Ba_{55}Sr_{49}TiO_3$</td>
<td>30</td>
<td>-70°C</td>
<td>5.82</td>
<td>414/463</td>
<td>0.78/4.4</td>
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<tr>
<td>$Ba_{55}Sr_{49}TiO_3$</td>
<td>60</td>
<td>-95°C</td>
<td>3.66</td>
<td>78/84</td>
<td>0.76/6.5</td>
</tr>
<tr>
<td>$Ba_{55}Sr_{49}TiO_3$</td>
<td>30</td>
<td>-45°C</td>
<td>9.54</td>
<td>478/527</td>
<td>0.75/12.1</td>
</tr>
<tr>
<td>$Ba_{55}Sr_{49}TiO_3$</td>
<td>60</td>
<td>-50°C</td>
<td>6.46</td>
<td>95/100</td>
<td>0.34/7.9</td>
</tr>
<tr>
<td>$Ba_{55}Sr_{49}TiO_3$</td>
<td>60</td>
<td>-55°C</td>
<td>9.99</td>
<td>117/118</td>
<td>1.48/12.9</td>
</tr>
</tbody>
</table>
CONCLUSIONS

ARL has developed low-cost, bulk oxide-ceramic composite ferroelectrics which provide a good combination of reduced dielectric constant and loss tangent while maintaining usable tunability. This paper described the use of these ferroelectric materials by NRL in developing affordable phased arrays. The cost savings are possible because of the bulk phase shifting approach that reduces the number of phase shifters along with their drivers and controls. The lens approach has the further advantages of being small, wideband and lightweight, and its bias control power requirements are low. Currently, research in further improving the ferroelectric material properties is under way at ARL. NRL is planning to demonstrate a small $(4\lambda_0 \times 4\lambda_0)$ ferroelectric lens next year.

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REFERENCES