Voltage-Controlled Ferroelectric Lens Phased Arrays

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***Abstract*— A new concept for phased arrays is proposed using a voltage-controlled ferroelectric lens. The ferroelectric lens concept uniquely incorporates bulk phase shifting—the array does not contain individual phase shifters—using ferroelectric material. This will reduce 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 significantly reduced by using row-column beam steering. Thus, the ferroelectric lens concept can potentially lead to low-cost phased arrays. This paper presents the ferroelectric lens concept, theoretical analysis and design, and experimental results. The results indicate that the ferroelectric lens concept is viable and sound. Various phased-array configurations using ferroelectric lens are included. A brief discussion on ferroelectric materials is included along with information on a U.S. Department of Defense program to improve ferroelectric materials.**

***Index Terms*— Bulk phase shifting, ferroelectric materials/devices, lens antennas, phased arrays.**

I. Introduction

PHASED-ARRAY antennas can steer transmitted and received signals without mechanically rotating the antenna. Each radiating element of a phased array is normally connected to a phase shifter and a driver, which determine the phase of the signal at each element to form a beam at the desired angle. The most commonly used phase shifters are ferrite and diode phase shifters. Phase shifters using ferroelectric materials have been proposed [1], [2]. The cost of a phased array mainly depends on the cost of phase shifters and drivers. A typical array may have several thousand elements and that many phase shifters and drivers; hence, it is very expensive. Therefore, reducing the cost and complexity of the phase shifters, drivers, and controls is an important consideration in the design of phased arrays. The phased array reported here uniquely incorporates bulk phase shifting—the array does not contain individual phase shifters—using ferroelectric material. This will reduce 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 significantly reduced by using row–column beam steering. Bulk phase shifting using diodes has been proposed [3] and reasonably developed [4] in the radant lens. The lens described here uses voltage-controlled ferroelectric, which introduces analog phase shift rather than digital phase shift as in the radant lens. The ferroelectric lens has the further advantages of smaller lens thickness, higher power handling capability, simpler beam steering controls, and it uses less power to control the phase shift compared to the radant lens. Thus, it leads to low-cost phased arrays. However, it should be noted that the use of row–column steering may limit the level of sidelobes that can be achieved. For the present study, it is assumed that ultralow side lobes are not a requirement and that row–column phase control can be used to significantly reduce the phased-array cost.

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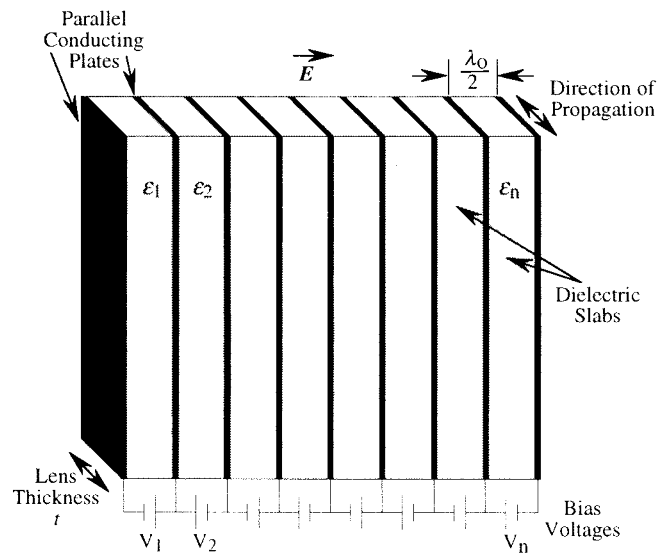


Fig. 1. Basic configuration of the ferroelectric lens.

II. Description of Ferroelectric Lens and Its Operation

The main feature of the antennas that use ferroelectric material is the change of permittivity with an applied dc control voltage. A lens type antenna is discussed in this paper. Fig. 1 shows a dielectric lens made up of dielectric slabs sandwiched between conducting plates. Dielectric slabs are made up of ferroelectric material whose dielectric constant can be changed by applying and varying the dc electric field (dc voltage sources $V_1,\ V_2 \ldots V_n$ are used for this purpose, as shown in Fig. 1). If a plane wave is incident on one side of the lens with RF electric field $\mathbf{E}$ normal to the conducting plates, the beam coming out on the other side of the lens can be scanned in the $\mathbf{E}$-plane if a linear phase gradient is introduced along the $\mathbf{E}$-plane direction by adjusting the voltages $V_1,\ V_2, V_3, \cdots V_n$. The corresponding dielectric constants are shown as $\varepsilon_1,\ \varepsilon_2, \varepsilon_3 \cdots \varepsilon_n$ in Fig. 1.

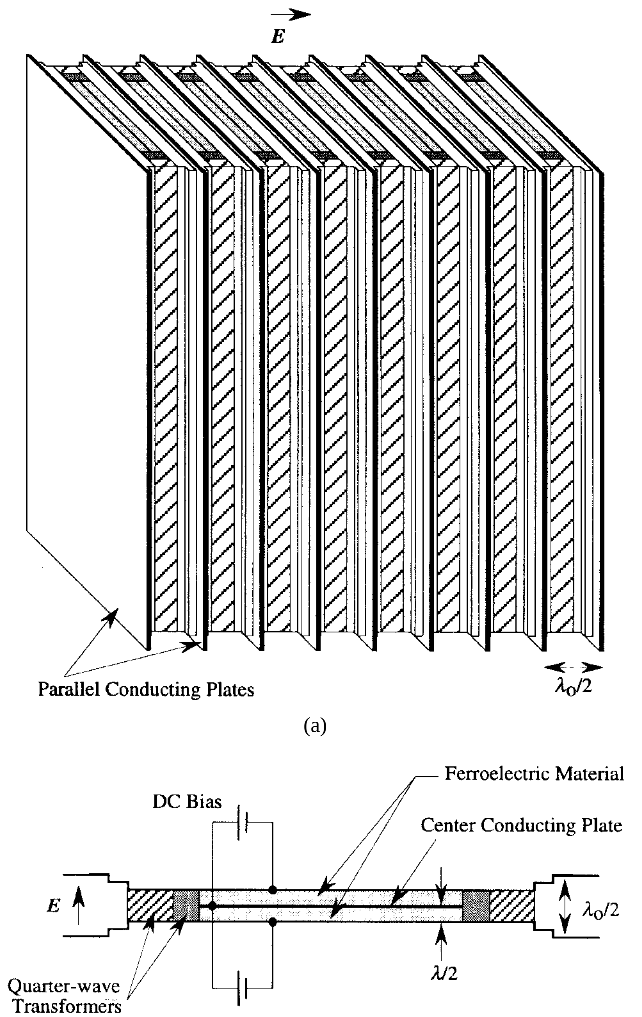


Fig. 2. (a) A more practical configuration of the ferroelectric lens. (b) Top view of one column.

Fig. 1 is used to illustrate the principle of operation of a ferroelectric lens. However, it has some limitations. To reduce the lens complexity and weight, the number of dc control voltages and the number of conducting plates need to be minimized. This can be achieved by selecting the separation between the conducting plates to be slightly less than $\lambda_o/(1+\sin\phi_s)$, similar to interelement spacing in any phased array in order to avoid grating lobes, where λ_o is the free-space wavelength, and ϕ_s is the maximum scan angle. Normally, the space between the conducting plates would be $\sim\lambda_o/2$. However, in a ferroelectric lens, this space is filled with a high dielectric constant ferroelectric material and so the space between the plates is much larger than $\lambda/2$, where λ is the wavelength in the ferroelectric. This means that higher order modes may propagate. Therefore, to eliminate the problem with higher order modes, the spacing between the conducting plates should be kept to less than $\lambda/2$. In addition, there should be some type of impedance matching arrangement to match the lens surface to free-space.

Fig. 2 shows a more practical lens configuration. This configuration has several advantages over the basic configuration of Fig. 1. A stepped configuration is used for impedance matching to reduce the amount of dielectric material, to eliminate higher order mode propagation, and to reduce the bias voltage necessary to create a certain amount of dc electric field intensity within the ferroelectric material. Quarter-wave dielectric transformers are used for impedance matching of the empty waveguide region to the ferroelectric-loaded waveguide region. More than one transformer may be needed depending on the value of the dielectric constant of the ferroelectric material and the degree of matching needed. A further refinement is also shown in Fig. 2. This refers to the way the dc bias voltage is applied to the ferroelectric material. An additional center conducting plate is used to bifurcate the ferroelectric material. The dc voltage is applied between this center conducting plate (recessed with respect to parallel plates) and the parallel plates. Since the dielectric material is bifurcated, only half the dc voltage needs to be applied to produce the same dc electric field intensity. It is this dc electric field intensity that controls the dielectric constant of the ferroelectric. In addition, the parallel plates are at ground potential. This makes the handling of the lens safer.

The lens thickness needed to use the lens as a scanning antenna can be determined as follows. Let t be the lens thickness as shown in Fig. 1. Let the dielectric constant of any one dielectric slab be $\varepsilon_{r,\max}$ when no bias voltage is applied. The dielectric constant of a ferroelectric decreases as the bias voltage is increased. Let $\varepsilon_{r,\min}$ be the dielectric constant when maximum dc bias is applied. The phase introduced by the slab when no bias voltage is applied is given by

$$\phi_{\max} = \frac{2\pi}{\lambda_o} t\sqrt{\varepsilon_{r,\max}}. \tag{1}$$

Similarly, the phase introduced by the same slab when maximum bias voltage is applied is given by (note: dielectric constant decreases with applied bias voltage)

$$\phi_{\min} = \frac{2\pi}{\lambda_o} t\sqrt{\varepsilon_{r,\min}}. \tag{2}$$

Then, the maximum phase change when the maximum bias voltage is applied is

$$\phi_{\max} - \phi_{\min} = \frac{2\pi}{\lambda_o} t(\sqrt{\varepsilon_{r,\max}} - \sqrt{\varepsilon_{r,\min}}). \tag{3}$$

For scanning applications, this maximum phase change should be equal to 2π (as in the case of a phase shifter used in a scanning array), hence (3) becomes

$$2\pi = \frac{2\pi}{\lambda_o} t(\sqrt{\varepsilon_{r,\max}} - \sqrt{\varepsilon_{r,\min}}). \tag{4}$$

So, the thickness of the ferroelectric material needed (in the direction of propagation) to obtain 360° phase shift is

$$t = \frac{\lambda_o}{\sqrt{\varepsilon_{r,\max}} - \sqrt{\varepsilon_{r,\min}}}. \tag{5}$$

Tunability can be defined for a ferroelectric as the fractional change in the dielectric constant with applied dc bias voltage or

$$\text{Tunability} = \frac{\varepsilon_{r,\max} - \varepsilon_{r,\min}}{\varepsilon_{r,\max}}. \tag{6}$$

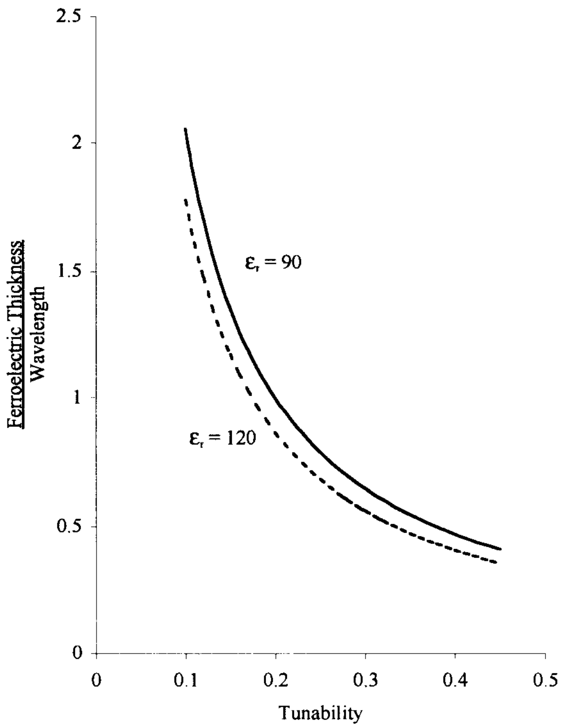
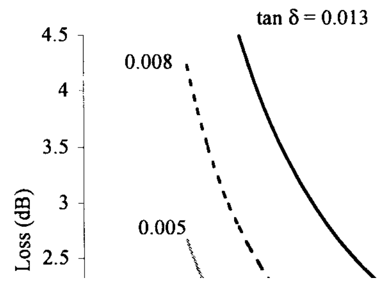


Fig. 3. Amount of ferroelectric needed for 360° phase shift.



Now (5) can be written in terms of tunability as

$$\frac{t}{\lambda_o} = \frac{1}{\sqrt{\varepsilon_{r,\max}}[1 - \sqrt{1 - \text{tunability}}]}. \tag{7}$$

So, the thickness of the ferroelectric material needed is a function of the dielectric constant and the tunability of the ferroelectric and the wavelength. The relationship shown in (7) is illustrated in Fig. 3 for typical ε_r of 90 and 120. Additional discussion on this relationship is included later.

Also, it can be shown [5] that the attenuation constant for a uniform plane wave propagating in a low-loss dielectric is

$$\alpha(\text{dB}) = 27.3 \tan\delta \sqrt{\varepsilon_r} \frac{t}{\lambda_o} \tag{8}$$

where $\tan\delta$ is the loss tangent. Using (7), we see that in order to obtain 360° phase shift, the dielectric loss through the ferroelectric is

$$\alpha(\text{dB})/360^\circ = \frac{27.3 \tan\delta}{1 - \sqrt{1 - \text{tunability}}}. \tag{9}$$

It may be noted that the lens loss is independent of the ferroelectric permittivity and depends only on its loss tangent and tunability. This equation is plotted in Fig. 4. It can also be approximated by using the Binomial series as

$$\alpha(\text{dB})/360^\circ \cong \frac{55 \tan\delta}{\text{tunability}}. \tag{10}$$

In general, the ferroelectrics with higher ε_r offer higher tunability, which is desired to reduce the lens thickness. However, the lens matching to free-space is easier for smaller ε_r. Therefore, a compromise is needed between reducing the lens thickness (to reduce overall lens size) and achieving reasonable impedance match to reduce reflections from the