New Phase Shifters and Phased Antenna Array Designs Based on Ferroelectric Materials and CTS Technologies

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***Abstract* -- As the search continues for low-cost and high-performance components for the front-end devices for wireless communications systems, focus has been on the use of MEMS technology; but some attention has recently been given to exploring new and innovative designs based on the Ferroelectric and the Continuous Transverse Stubs (CTS) technologies. In this paper we present new phase shifter designs and an integrated phased array antenna system based on the use of multilayer Ferroelectric materials. Simulation results show that with the appropriate selection of the materials properties and the dimensions of the multilayer dielectric system, insertion losses may be reduced by as much as a factor of 100. These results also show that while only a slight reduction (15%) in the maximum achievable tunability was observed, it was possible to achieve significant improvement in the impedance matching characteristics. A procedure to enhance the radiation efficiency from an integrated Ferroelectric/CTS phased antenna array design will be described and specific array designs will be discussed.**

I. INTRODUCTION

Filters, phase shifters, and phased antenna array designs based on MicroElectroMechanical (MEMS) devices have recently received considerable attention [1-3]. The low cost, high performance, and successful operation at higher microwave and even millimeter-wave frequencies have certainly sparked a significant research activity, and it is fair to state that the MEMS technology is the focus for the Reconfigurable Aperture DARPA program as well as others [4]. Ongoing research activities continue to address remaining limitations of the MEMS technology including the required relatively high biasing voltage, stiction, dielectric breakdown, packaging, limited capacitance tunability, and lower q inductors for filter designs. Ferroelectric materials, on the other hand, are characterized by change in permittivity with an applied dc bias voltage. This change in permittivity can be used to change the electrical length of a transmission line and hence in the design of low-cost phase shifters. Results from a comparative study between the Ferroelectric and MEMS technologies are summarized elsewhere [5-8].

A commonly used Ferroelectric material in this application is $Ba_x Sr_{1-x} TiO_3$ (BSTO) and recent advances in development of these materials have resulted in lowering the dielectric constant (~100), decreasing the loss tangent (tan $\delta < 0.0009$), and in a significant increase in tunability as well as reduction in sensitivity of the material to temperature variations. It was, however, generally felt that phase shifter designs based on this technology, although low cost, still exhibit high insertion losses and that the integration of these phase shifters in an integrated phased antenna array system may still be cumbersome particularly when biasing circuits are included. It is, therefore, important that besides lowering the losses in the Ferroelectric materials, say, by Mn doping and reducing the sensitivity to temperature variation through baseline biasing, new phase shifting designs need to be developed as well as an effective procedure for integrating them in a phased antenna array system.

In this paper we describe a new phase shifter design procedure that is based on the use of multilayer dielectric materials including a middle layer of highly tunable Ferroelectric materials. The effectiveness of this approach in reducing the insertion losses will be evaluated and its impact of the device tunability will be quantified. An effective procedure for integrating these phase shifters in a phased antenna array design using the CTS technology will also be described and the performance of design examples of CTS systems will be discussed [9]. Results of reflection characteristics, insertion losses, and radiation efficiency will all be presented.

II. Low-Cost and Low-Loss Phase Shifter Design

The proposed phase shifter design is based on a section of transmission line filled with multilayer dielectric that includes the voltage tunable Ferroelectric materials. Figure 1 shows a schematic of the proposed arrangement whereby the Ferroelectric material is separated from the transmission line conductors by a low dielectric constant material such as Teflon.

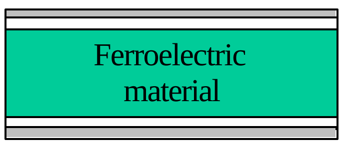

Fig. 1. Schematic of the multilayer dielectric in a parallel plate transmission line. A highly tunable dielectric material is insulated from the conductors through a thin layer of Teflon.

It is expected that such an arrangement will tend to concentrate the microwave energy in the core Ferroelectric material and hence would result in a reduction in the surface current on the transmission line conductors. This would, in turn, reduce the conductor losses and in addition increase the characteristic impedance, thus improving the matching characteristics of these devices. Table I shows simulation results where it may be seen that the reduction in the conductor losses is as high as by a factor of 100.

TABLE I
RESULTS OF THE CONDUCTOR LOSSES IN A MULTILAYER TRANSMISSION LINE STRUCTURE.

(A) THE REFERENCE CASE WITH LINE FULLY LOADED WITH FERROELECTRIC MATERIAL

ε_r	Normalized beam steering*	Normalized Loss*	Z_0(100mm width)
400	1	1	0.0452

(B) MULTILAYER LOADED LINES. FOR THE CASE OF ε_r = 400, REDUCTION OF LOSSES BY A FACTOR OF 100 WAS ACHIEVED. H (HEIGHT OF WAVEGUIDE) = 0.48 MM, 0.01 MM AIR GAP ON EACH SIDE OF FERROELECTRIC MATERIAL AND FERROELECTRIC MATERIAL HEIGHT = 0.46 MM.

ε_r	Normalized beam steering*	Normalized Loss*	Z_0(100mm width)
100	0.5747	0.18	0.3260
200	0.6882	0.0181	0.6488
400	0.8439	0.0011	1.3663

Equally important to note is that, subject to using Ferroelectric material of higher dielectric constant (e.g., 400), it may be possible to maintain a high percentage (85%) of the achievable tunability when loading with the transmission line loaded with a single layer of Ferroelectric material. Additional design improvement was also achieved by using wedge-shaped Ferroelectric slab (see Fig. 2) which helped improve the impedance matching characteristics. Figure 3 shows the S_{11} vs. frequency.

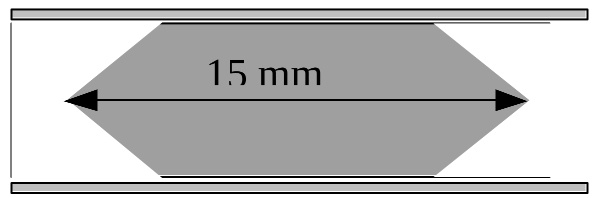

Fig. 2. Schematic of the feed geometry to improve the impedance matching characteristics.

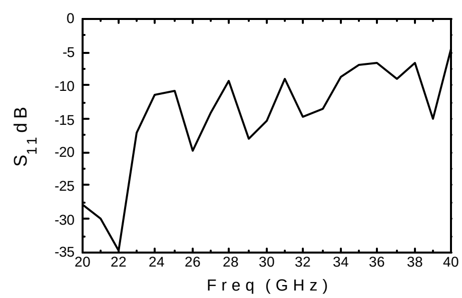

Fig. 3. S_{11} vs. frequency for the feed structure shown in Figure 2.

III. Phased Antenna Array Designs Using Integrated Ferroelectric Material and CTS Technology

Integrating the phase shifting characteristics of a tunable section of transmission line loaded with multilayer dielectric, together with radiating stubs in a CTS-type design arrangement, provide a significant opportunity for the design of a low-cost phased antenna array with beam steering capability. A schematic of one of the implemented designs is shown in Fig. 4 and the results of its simulated characteristics is given in Table I (B). The resulting radiation patterns are shown in Fig. 5.

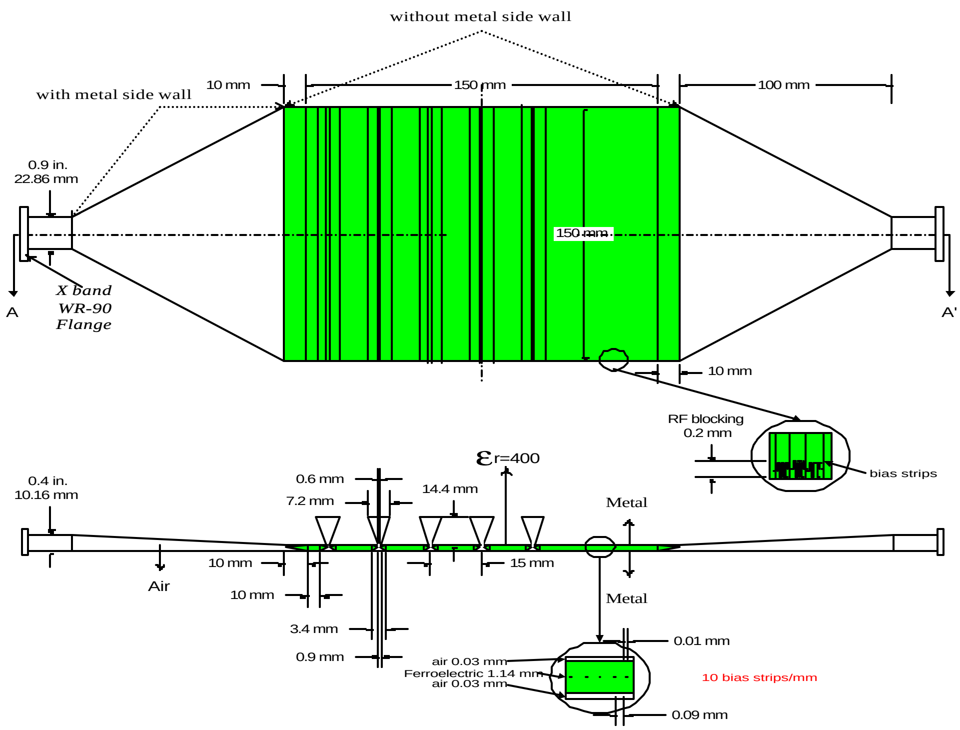

Fig. 4. Schematic of an X-band five-element antenna array using CTS technology and multilayer loaded feed structure.

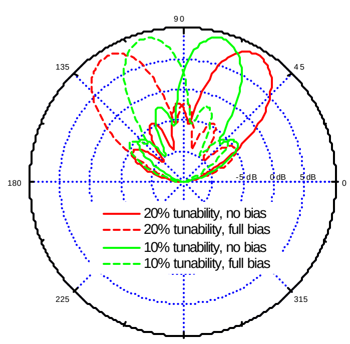

Fig. 5. Radiation pattern of the five-element CTS antenna array. The figure illustrates the steering capability with the use of Ferroelectric materials. 10 GHz, 90% radiation, 5 elements, element distance 15 mm, 20% tunability, ±30° peak angle, ±43° 3dB cover angle, 10% tunability, ±15° peak angle, ±27° 3dB cover angle, (at 0°) Directivity (D) =9.59 dB; (at ±15°) D=9.58 dB; and at±30°, D=9.35 dB.

Additional design issues in the proposed antenna system such as biasing and avenues for reducing sensitivity to fabrication tolerances will also be discussed. It will be shown that the inclusion of multilayers of conductor strips inside the Ferroelectric material layer not only reduces the required biasing voltage through this multistage operation but also has a minimal effect on the propagation losses in the material. Clearly inclusion of conductors would increase losses, but the amount of increase is certainly acceptable as will be graphically demonstrated. It will also be shown that by opening an air gap in the Ferroelectric material just beneath the radiating stubs, significant enhancement in the radiation efficiency will be achieved in addition to reduced sensitivity to fabrication errors as we will be dealing with larger wavelengths in the air region.

IV. CONCLUSIONS

A new phase shifter design and low-cost phased antenna array designs were described. These designs were based on the use of multilayer dielectric loaded transmission lines and an integrated antenna array design approach based on the CTS technology. The multilayer dielectric materials included a highly tunable Ferroelectric material, but separating the BSTO material from the transmission line conductors proved to be critical in providing significant reduction in losses while maintaining significant fraction of the tunability. This arrangement also resulted in an impedance matching advantage, and the proposed integrated approach for the phased antenna array will have significant cost reduction and fabrication advantages over available phased array design techniques. Results for the insertion losses, reflection coefficient, and radiation characteristics of an X-band antenna array were described.

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