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, some focus has been placed on exploring new and innovative designs based on ferroelectric technology. In this paper, we present new phase-shifter designs and an integrated phased-array antenna system based on the use of multilayer ferroelectric materials and the continuous transverse stub (CTS) technologies. 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 impedance-matching characteristics. A procedure to enhance the radiation efficiency from an integrated ferroelectric/CTS phased antenna array design is described and specific array designs are discussed.**

***Index Terms*—Antenna array, continuous transverse stub, ferroelectric material, microstrip, multilayer dielectrics, phase shifter.**

I. INTRODUCTION

FILTERS, phase shifters, and switches for phased-array antenna designs based on microelectromechanical system (MEMS) devices have recently received considerable attention [1]–[3].[1] The low-cost, high-performance, and successful operation at higher microwave and even millimeter-wave frequencies has certainly sparked significant research activities, and ongoing research activities continue to address remaining limitations of MEMS technology, including the relatively high required bias voltage, stiction, dielectric breakdown, packaging issues, 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 [4]–[7].

A commonly used ferroelectric material in this application is $Ba_xSr_{1-x}TiO_3$ (BSTO), and recent advances in the development of these materials have resulted in lowering the dielectric constant (∼100), decreasing the loss tangent ($\tan\delta < 0.0009$), increasing the tunability, and reducing the sensitivity of the material to temperature variations. It was, however, generally felt that phase-shifter designs based on this technology, although low cost, still exhibited unacceptably high insertion losses. Additionally, the integration of these phase shifters in an integrated phased-array antenna 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-shifter designs need to be developed, as well as an effective procedure for integrating them in a phased-array antenna system.

The continuous transverse stub (CTS) technology was developed in the early 1990's, and its highly publicized benefits include compact size, light weight, low loss, and high directivity [8]. In addition, high gains were achieved along with greater dimensional insensitivity, which reduced fabrication costs [9].

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 material. The effectiveness of this approach in reducing the insertion losses is evaluated and its impact on device tunability has been quantified. An effective procedure for integrating these phase shifters in a phased-array antenna design using CTS technology is also described and the performance of design examples of CTS systems will be discussed [10]. Simulated performance in terms of reflection characteristics, insertion losses, and radiation efficiency is 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 multiple layers of dielectrics, including the voltage-tunable ferroelectric material. Fig. 1 shows a

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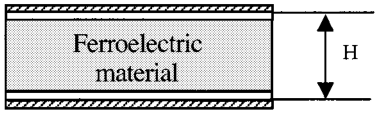


Fig. 1. Schematic of the multilayer dielectric in a parallel-plate transmission line. A highly tunable dielectric material is insulated from the conductors through a thin layer of Teflon.

TABLE I
RESULTS OF THE CONDUCTOR LOSSES IN A MULTILAYER TRANSMISSION-LINE STRUCTURE. FOR THE CASE OF $\varepsilon_r = 400$, 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 THE FERROELECTRIC MATERIAL, AND FERROELECTRIC MATERIAL HEIGHT $= 0.46$ mm. RESULTS WERE NORMALIZED TO PARALLEL-PLATE STRUCTURES WHEN FULLY FILLED WITH THE CORRESPONDING VALUES OF ε_r

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

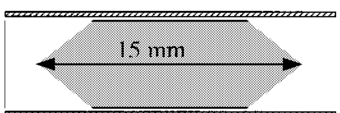


Fig. 2. Schematic of the feed geometry to improve the impedance-matching characteristics.

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.

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 reduces the conductor losses and, in addition, increases the characteristic impedance, thus improving the matching characteristics of these devices. Table I shows simulation results where it may be seen that it is possible to achieve reduction in the conductor losses by as much as a factor of 100.

Equally important to note is that, subject to using ferroelectric material of higher dielectric constant (e.g., $\varepsilon_r = 400$), it may be possible to maintain a high percentage (85%) of the achievable tunability when loading with the multidielectric layer arrangement including a single layer of ferroelectric material. Additional design improvement was achieved using a wedge-shaped ferroelectric slab (see Fig. 2) that helped improve the impedance matching characteristics. Fig. 3 shows the variation of S_{11} with frequency, where the broad-band nature of the proposed phase-shifter design should be emphasized (20–34 GHz, for $S_{11} < -10$ dB).

Figs. 4 and 5 illustrate the simulated characteristics of a parallel-plate transmission line when loaded with the multidielectric arrangement including a ferroelectric layer. Fig. 4 shows the significant reduction in the conductor losses when the multidielectric layer arrangement is used. As may be noted, regardless of the height of the transmission-line structure, a reduction by a factor of four or more (particularly for larger heights) may be achieved. It is also worth mentioning that this case was calculated for ferroelectric material of $\varepsilon_r = 500$ and $\tan\delta = 0.0009$, which resulted in conductor losses dominating the total transmission losses. For other types of ferroelectric materials that may have larger values of loss tangent, the contribution of the conductor losses to the total losses may be less significant and, hence, the multilayer arrangements will provide a reduced level of advantage [11]. One might wonder why the relative reduction in the conductor losses is more significant when larger heights

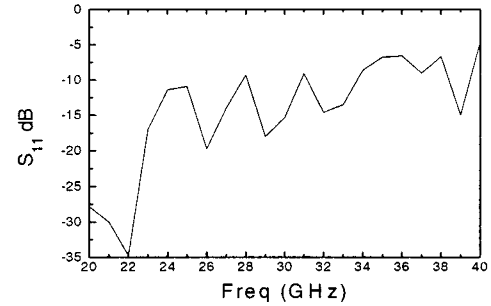
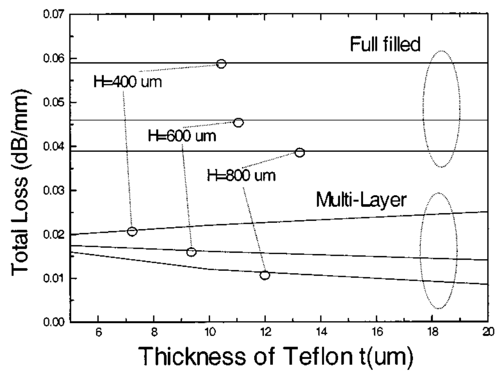
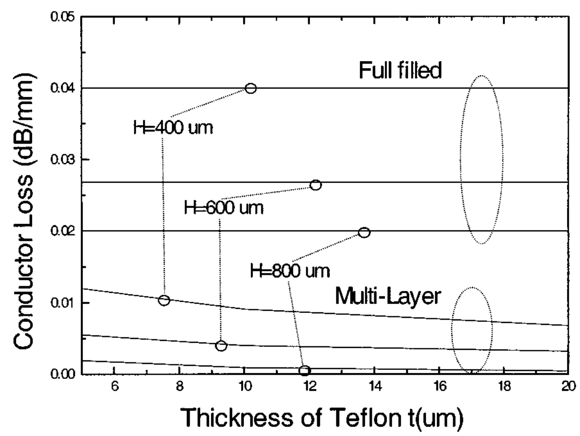


Fig. 3. S_{11} versus frequency for the feed structure shown in Fig. 2.



(a)



(b)

Fig. 4. (a) Total and (b) conductor losses for two parallel-plate transmission-line phase shifters, one fully filled with ferroelectric material and one filled with multilayer dielectric material.

TABLE II
EFFECT OF VARYING THE THICKNESS OF THE FERROELECTRIC MATERIAL IN A MULTILAYER PARALLEL-PLATE WAVEGUIDE ARRANGEMENT. THE THICKNESS OF THE AIR LAYER WAS KEPT CONSTANT AND EQUAL TO 0.01 mm, AND THE DIELECTRIC CONSTANT OF THE FERROELECTRIC MATERIAL WAS ASSUMED 400 AND $\tan\delta = 0.0009$

Ferroelectric	Normalized beam steering	Normalized Loss	Z_0 (100 mm width)
0.16 mm	0.1873	0.0536	0.1434
0.26 mm	0.4376	0.022	0.4145
0.46 mm	0.8439	0.0011	1.3663

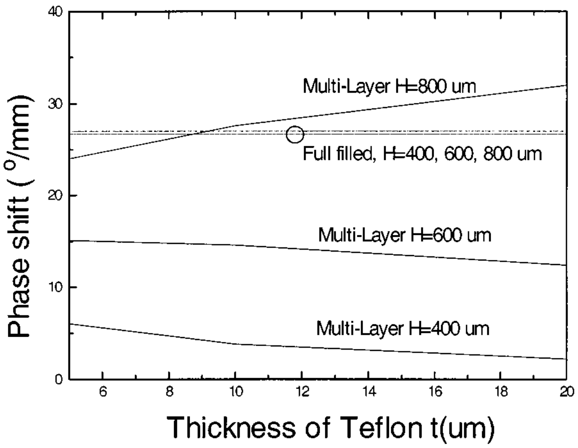


Fig. 5. Phase shift for a parallel-plate phase shifter with multilayer ferroelectric material. The phase shift is compared between biased and unbiased states. The height of the parallel-plate waveguide was varied.

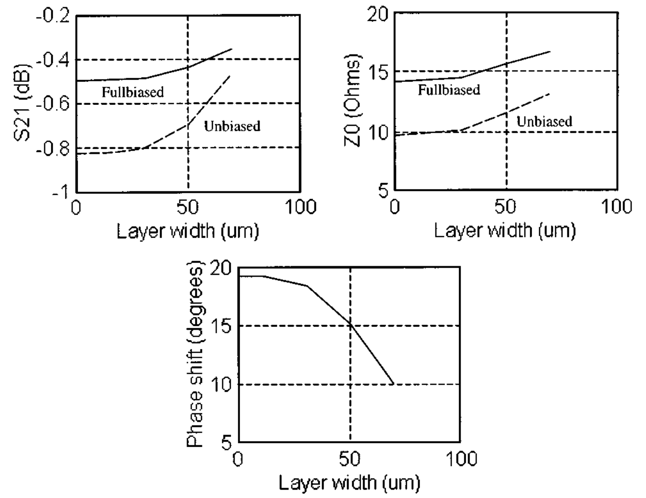


Fig. 6. Microstrip line with ferroelectric substrate. The low dielectric layer has a depth of 0.5 μm and the dielectric constant is ten. Frequency $= 3$ GHz and the width of the layer was varied.

of the parallel-plate waveguide are used. As previously mentioned, larger heights result in larger characteristic impedance values and, hence, lower values of the conductor losses to begin with. This is true, but results in Table II show that the increase in the height of the parallel-plate waveguide more than compensates for the reduction in the characteristic impedance that results from the increase in the effective dielectric constant of the multilayer dielectric arrangement. Hence, an overall increase in the impedance value is observed, and a reduction in the overall value of the conductor losses is achieved. This observation was further confirmed by examining finite-difference time-domain (FDTD) results and the detailed values of the electric and magnetic fields confined in the ferroelectric and air regions in the multilayer dielectric arrangement. Fig. 5 shows the phase shift that may be accomplished when the multilayer dielectric arrangement is used. It is to be noted that the multilayer arrangement results in a reduction in the phase shift between the biased and unbiased condition, and this clearly represents the tradeoff between the reduction in the total propagation losses and the achievable phase shift between the biasing conditions.

Fig. 6 illustrates the general tradeoffs involved in the design of ferroelectric-loaded microstrip transmission-line phase shifters. As may be seen, the implementation of the multilayer structure decreases the tunability and, hence, the achievable phase shift. This disadvantage is associated with two separate, but related advantages including the increase in the characteristic impedance Z_0 and an improvement in the transmission coefficient S_{21}. The reduction in the biasing with the reduction in the thickness of the ferroelectric layer (i.e., increase in thickness of the low dielectric layer) is yet another added advantage in the design and optimization of the microstrip phase shifter structure.

III. PHASED ANTENNA ARRAY DESIGNS USING INTEGRATED FERROELECTRIC MATERIAL AND THE 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, provides a significant opportunity in the design of a low-cost phased-array antenna with beam-steering capability. A schematic of one of the implemented designs is shown in Fig. 7, and its simulated characteristics together with the resulting radiation patterns are shown in Fig. 8. The CTS array shown in Fig. 7 is an X-band five-element array with multilayer dielectric loading. Also shown in this figure is a possible voltage biasing approach, whereby 0.01-mm biasing wires were connected to each other and to the dc-biasing voltage through RF blocking inductors.

Additional design issues in the proposed antenna system—such as additional losses due to biasing and avenues for reducing sensitivity to fabrication tolerances—were also considered in the design shown in Fig. 8. It is shown that the inclusion of multilayers of conductor strips inside the ferroelectric material layer not only reduces the required biasing voltage through this multistage series operation, but also has a minimal effect on the propagation losses in the material [11]. Typical bias requirement for the ferroelectric materials is about 2–3 V per micrometer of the material thickness. It is also

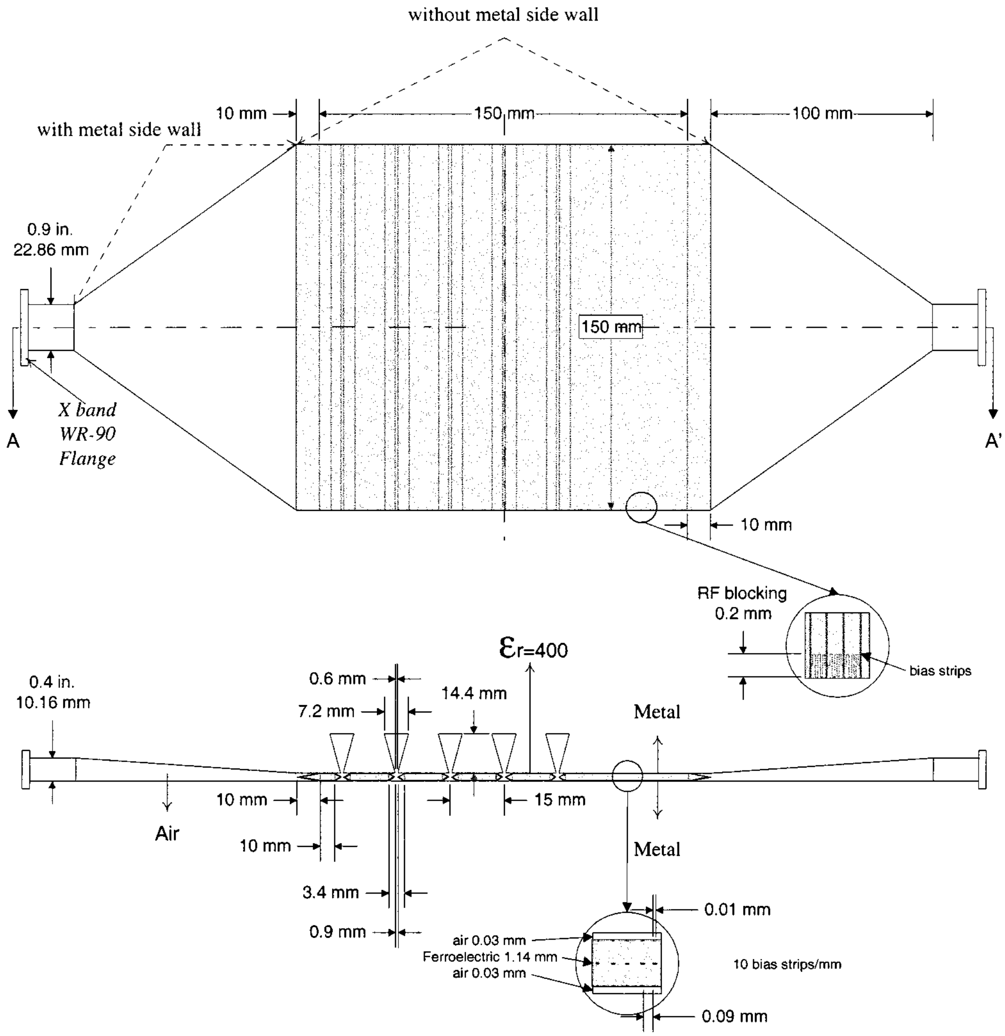


Fig. 7. Schematic of an X-band five-element antenna array using CTS technology and multilayer loaded feed structure.

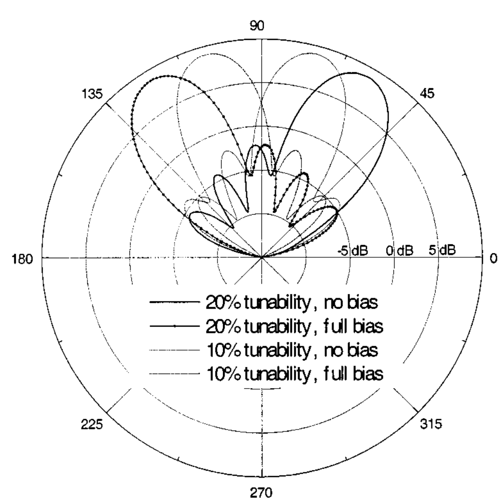
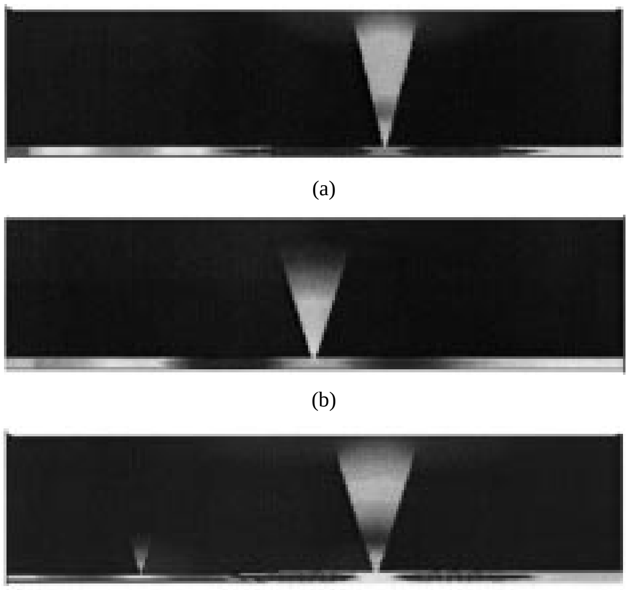


Fig. 8. Radiation pattern of the five-element CTS antenna array shown in Fig. 7. This figure illustrates the steering capability with the use of ferroelectric materials. At 10 GHz, 90% radiation is achieved. Element spacing is 15 mm. For 20% tunability, the peak angle beam width is $\pm 30°$, 3-dB cover angle is $\pm 43°$; for 10% tunability, the peak angle beam width is $\pm 15°$, 3-dB cover angle is $\pm 27°$. Directivity $(D) = 9.59$ dB (at 0°), $D = 9.58$ dB (at $\pm 15°$), and $D = 9.35$ dB (at $\pm 30°$).

shown that by opening an air gap in the ferroelectric material just beneath the radiating stubs, significant enhancement in the radiation efficiency was achieved, in addition to reduced sensitivity to fabrication tolerances, particularly at the base of the radiating stubs. The latter effect is a consequence of dealing with the larger wavelengths in an air region beneath the stub rather than that of a high dielectric one (much shorter wavelength) if the ferroelectric material was to be placed beneath the stubs.

Fig. 9 shows another innovative design of the integrated CTS and ferroelectric material technologies. This figure illustrates a possible realization of a multiband CTS array whereby a high-frequency radiating stub was placed after the input port of the array, while the low-frequency radiating stub was placed after the high-frequency one. The idea is that the high-frequency signals would be radiated by the high-frequency stub and limited energy would reach the low-frequency stub (hence, low S_{11} at the higher frequency). If designed properly, the high-frequency stubs should be passing on the low-frequency signal (high S_{21} at the lower frequency) and much of this low-frequency signal would be radiated by a properly designed low-fre-



(a)

(b)

(c)

Fig. 9. Multiband CTS array. (c) combines a high-frequency CTS operating at 30 GHz and a low frequency one operating at 10 GHz. The radiation and transmission characteristics of the high-frequency CTS (30 GHz) are shown in (a) and (b). (a) Design at 30 GHz, simulated performance at 30 GHz. $S_{11} = -13.1$ dB, $S_{21} = -2.3$ dB, 36% radiation. (b) Design at 30 GHz, simulated performance at 10 GHz. $S_{11} = -9.0$ dB, $S_{21} = -0.7$ dB, 2.3% radiation. (c) Simulated performance at 10 GHz. $S_{11} = -5.26$ dB, $S_{21} = -3.28$ dB, 24% radiation.

quency stub. S-parameters for a simulated multiband design are given in Fig. 9. While additional simulation is needed to optimize the performance of the overall system, this figure shows acceptable characteristics at the lower frequency band even with having an intermediate high-frequency stub between the input and the low-frequency stub.

IV. Conclusions

New phase-shifter and low-cost phased-array antenna designs have been 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 sandwiched between thin layers of Teflon. Separating the BSTO material from the transmission-line conductors proved to be critical in providing significant reduction in losses while maintaining a 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 have also been described.

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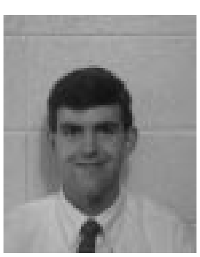

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