Novel High Performance Low Cost Phase Shifters Design Based on the Ferroelectric Materials Technology Using the WIPL-D Code

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Abstract: A novel approach in ferroelectric phase shifter designs using $Ba_xSr_{1-x}TiO_3$ (BSTO) films in a multilayer dielectric environment is described. It is shown that by including a low loss dielectric layer (SiO_2) between the coplanar waveguide conductors and the ferroelectric material, significant reduction in the insertion loss can be achieved and as high as three fold increase in the figure of merit (^{o}/dB) is possible to realize. The phase shifter design involves a BSTO thin film over a $LaAlO_3$ substrate for low strain and lattice match. A reduction in the insertion loss by approx. 5 dB/cm for high εr ferroelectric materials, and a decrease in return loss by 20 dB were observed at 10 GHz. Design tradeoffs and fabrication aspects will be discussed.

Keywords: $BaSrTiO_3$, coplanar, ferroelectric, low cost, multilayer dielectrics, phase shifters.

1. Introduction

To enable and fully develop next generation of integrated (terrestrial wireless, satellite, and GPS) and broadband wireless communications technology and realize its much anticipated benefits in commercial and military applications, it is critically important that low cost and high gain phased antenna arrays with beam steering capability be developed. These antennas require thousands of phase shifters and hence some focus need to be placed on exploring new and innovative designs for low cost and high performance microwave and millimeter wave phase shifters. Ferrite phase shifters are often used in a typical phased-array antenna system and thousands of phase shifters are needed to achieve the desired performance. Therefore, low-cost, compact phase shifters are required that can provide the full 360° range of phase shift while minimizing the associated insertion and mismatch losses. Present-day ferrite phase shifters maximize phase shift over a given length of the device by producing circularly polarized microwaves to interact with the magnetic dipole moments in a biased ferrite material. This is typically done by placing a longitudinally (i.e., in the direction of propagation) biased ferrite rod in the center of a waveguide. Although this technique produces the desired phase shift, it is costly to manufacture because of its extreme sensitivity to tolerances, and the need for matching networks at both the input and output ports. Recently our group developed a novel microstrip based Ferrite phase shifters that provided and maintained the desired high performance while displaying minimal sensitivity to manufacturing tolerances and hence achieved the desired low cost objective [1].

An alternative approach for developing low cost and high performance tunable microwave devices and phase shifters is based on the utilization of ferroelectric materials. These materials 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 say a transmission line and, hence, in the design of low-cost phase shifters. A specific ferroelectric material that is commonly used in these applications 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 (~0.0009), increasing the tunability (~20%), and in reducing the sensitivity of the material properties 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 and impractical low input impedance values. To help overcome these difficulties, our group developed a new phase-shifter design that is based on the use of multilayer dielectric materials including a middle layer of highly tunable ferroelectric material [2].

The effectiveness of this approach in reducing the insertion losses was evaluated in microstrip type structures and the impact of the multilayer design on the device tunability was quantified. It was observed that while significant reduction in the insertion losses (factor of 10) may be achieved using this multi-dielectric layers approach, and a significant fraction of the maximum tunability (85%) may be achieved, the device impedance continued to be impractically small due to the high dielectric constant values of the ferroelectric materials.

In this paper we describe an alternative approach that while still utilizing the ferroelectric technology and the novel approach of multilayer dielectric materials, it bases the implementation on the use of coplanar waveguides that is known to provide higher resiliency to change in impedance with the change in the dielectric material. It should be emphasized that while a similar approach has been recently described in the MTT Transactions [3], metallization was directly applied to the ferroelectric materials and hence unacceptably high insertion loss values were reported. In this paper we compare these available results with new simulations that utilize the novel multilayer dielectric design. Significant improvements were observed and higher figure of merit was achieved.

2. Simulated Models and Numerical Results

As mentioned earlier, the objective of the proposed simulation effort is to examine the feasibility of using coplanar waveguide structures together with the multilayer ferroelectric material technology to design and develop high performance phase shifters and other tunable microwave devices. Among the desirable characteristics are:

1. Low insertion losses
2. Large phase shift values per unit length
3. Good impedance matching characteristics
4. High figure of merit (^{o}/dB), and low cost including insensitivity to tolerance and practical and easy to implement biasing circuit

For the simulation purposes we implemented two coplanar designs. One is based on one-sided loading with the multilayer dielectric material, while the other is based on two-sided implementation of the multilayer dielectric loading. It is suggested that the two sided loading may result in capturing more of the fringing fields and would, hence, enhance the performance of the phase shifter.

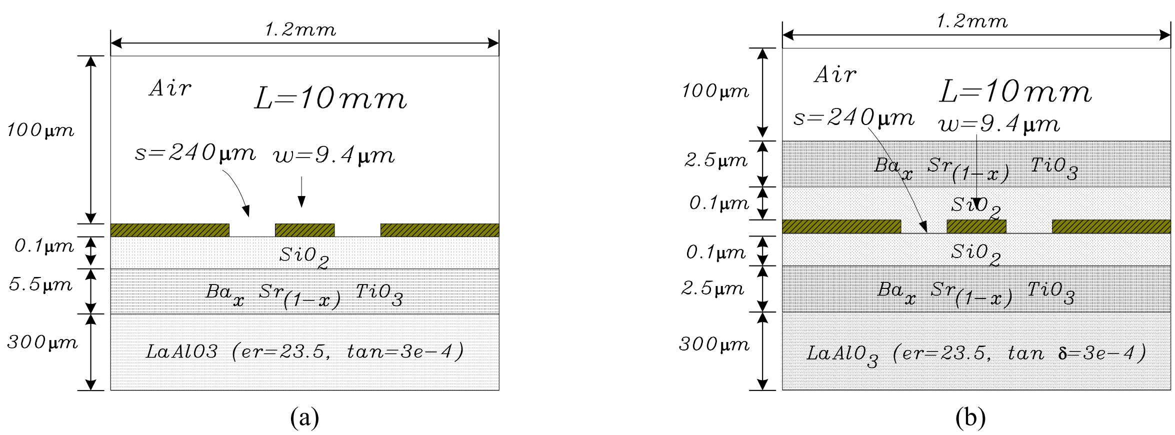


Fig. 1. Schematics of the cross sections for two cases of multilayer CPW designs. (a) incorporates a substrate only approach, while (b) incorporates both the sub super-strate configurations. The line length in both cases is 10 mm.

Fig. 1 shows the schematics of the proposed geometries where the conductor thickness is 0.1 μm and Table 1 shows comparison of the obtained results. As it may be observed, although the design in Fig. 1b out performed that in Fig. 1a, the differences are quite small and may not warrant the complications in the fabrication process.

Figure	Z_o, ε_r low	Z_o, ε_r high	α (dB/mm) ε_r low	α (dB/mm) ε_r high	ϕ(^{o})
1b	50.6, 441	45, 723	0.248	0.283	82
1a	51, 441	46, 723	0.243	0.275	75

Table 1: Simulation results comparing the change in characteristic impedance (Z_o), attenuation (α), and the phase shift (ϕ) for the two designs in Fig. 1

To demonstrate the advantages of using the multilayer dielectric approach, the geometry shown in Fig. 1a was simulated and the results were compared with recently published data [3]. Fig. 2 shows a cross section of a situation where the CPW conductors lie directly on the ferroelectric, where a 508 μm $LaAlO_3$ substrate was used under a 0.5 μm $Ba_{0.6}Sr_{0.4}TiO_3$ film [3]. In the proposed case shown in Fig. 1a, a 300 μm $LaAlO_3$ substrate was used together with a 5.5 μm $Ba_{0.6}Sr_{0.4}TiO_3$ film deposited over it, followed by a 0.1 μm layer of SiO_2 under the CPW.

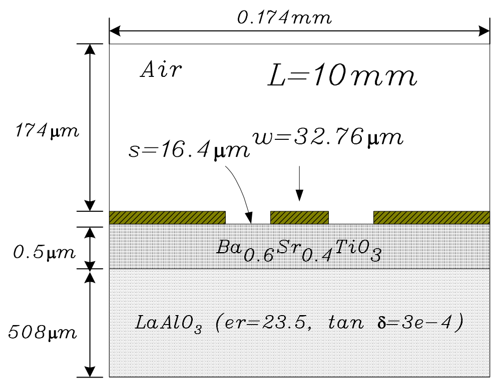
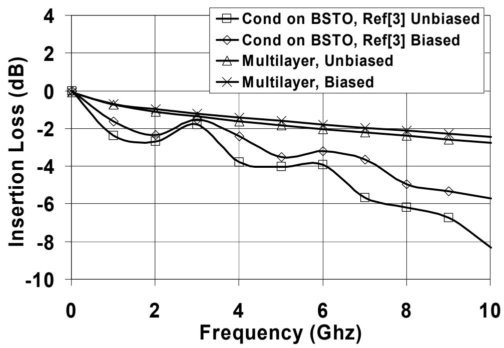


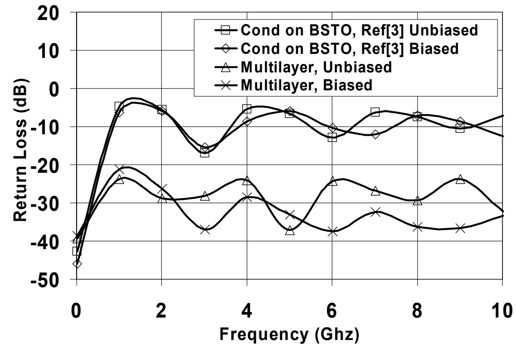
Fig. 2. Cross section of multilayered co-planar waveguides for X-band phase shifter applications for conductors directly on the ferroelectric material [3]. The dielectric constant of SiO_2 is 3.8 with tan δ of 1e-4 and the conductor thickness is 0.1 μm.

Fig. 3 shows simulation results of the insertion and return losses for the CPW architecture with $SiO_2/Ba_{0.6}Sr_{0.4}TiO_3$ on $LaAlO_3$ compared with the case of conductors directly on the ferroelectric material [3]. The line length was 10 mm and the permittivity of the BSTO material ranged from 723 (unbiased state ~ 0 V) to 441 (full bias state ~ 40 V) with a loss tangent of approximately 0.01. The results show an improvement in insertion loss by approx. 5 dB at 10 GHz for both dielectric cases. Significant improvements in the return loss may also be observed in Fig. 3b.

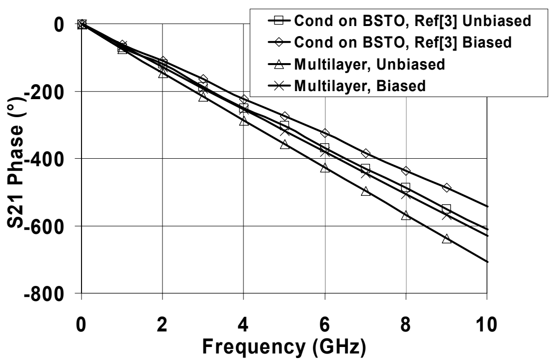
Fig. 3 also shows the phase of S21 results for both the proposed multilayer dielectric case and the literature data. As it may be observed from both Figs. 3c and 3d, the proposed approach significantly out performed the direct metallization on the ferroelectric material approach recently reported in [3]. The design configurations shown in Fig. 1a produced a figure of merit of over 26 ^{o}/dB at 10 GHz in addition to a significant improvement in insertion and return losses. It should be noted that for broadband applications the applied bias could be easily scaled with frequency to achieve the desired response.



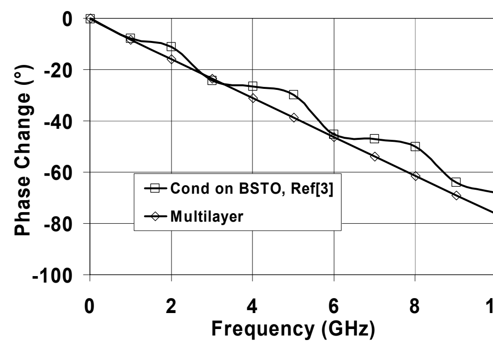
(a)



(b)



(c)



(d)

Fig. 3. (a) Insertion loss, (b) return loss, (c) S21 phase, and (d) phase change for multilayer ferroelectric over $LaAlO_3$ compared with conductors directly on $Ba_{0.6}Sr_{0.4}TiO_3$ [3]. The figures show reduction in insertion losses (a), improved return loss (b), and large change in phase of S21 and the total phase change (c) and (d). Results represent comparison between the multilayer approach and the direct conductor on BSTO case [3].

Simulated results using WIPL-D [4] and LINPAR [5], for the case with conductors directly on the ferroelectric film, agree very well with measured results from [3]. The simulated data provides an accurate analysis for modeling thin film ferroelectric materials with very high permittivity at X-band. Both simulation packages were used for the analysis of the multilayered ferroelectric structure.

3. Conclusions

A novel, high performance, and low cost phase shifter design is proposed and its performance was simulated and numerically evaluated. The proposed design is based on a multi-dielectric material CPW design and the utilization of ferroelectric material for achieving tuning and phase shifting. It is shown that by including a low loss thin dielectric layer (SiO_2) between the coplanar conductors and the ferroelectric materials, significant reduction in the insertion loss can be achieved (up to 5 dB) and as high as three fold increase in the figure of merit (^{o}/dB) is possible.

References

[1] R. K. Sorensen, M. F. Iskander, and J. J. Lee, “Low-cost Nonplanar Microstrip-line Ferrite Phase Shifter Utilizing Circular Polarization,” *Microwave and Wireless Components Letters*, accepted for publication, 2003.

[2] M. Iskander, Z. Zhang, Z. Yun, R. Isom, M. Hawkins, R. Emrick, B. Bosco, J. Synowczynski, and B. Gersten, “New phase shifters and phased antenna array designs based on ferroelectric materials and CTS technologies,” *IEEE Trans. Microwave Theory Tech.*, vol. 49, no. 12, Dec. 2001.

[3] C. Krowne, M. Daniel, S. Kirchoefer, J. Pond, “Anisotropic Permittivity and Attenuation Extraction From Propagation Constant Measurements Using an Anisotropic Full-wave Green’s Function Solver for Coplanar Ferroelectric Thin- Film Devices,” *IEEE Trans. Microwave Theory Tech.*. Vol. 50, no. 2, Feb. 2002.

[4] Kolundzija, B., Ognjanovic, J. and Sarkar, T., *WIPL-D: Electromagnetic Modeling of Composite Wire and Plates Structures – Software and User’s Manual*, Artech House, Boston, 2000.

[5] Djordjevic, A., Bazdar, M., Sarkar, T. and Harrington, R., *LINPAR for Windows: Matrix Parameters for Multiconductor Transmission Lines – Software and User’s Manual,* Artech House, Boston, 1999.

