High Performance Low Cost Ferroelectric Phase Shifters Designed for Simple Biasing

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Abstract: A novel approach in ferroelectric phase shifters design using $Ba_xSr_{1-x}TiO_3$ (BSTO) films in a multilayer dielectric coplanar waveguide structure is described. By including a low loss dielectric layer (SiO_2) between the coplanar waveguide conductors and the ferroelectric material in conjunction with a via to allow the signal conductors to contact the ferroelectric layer to employ biasing, significant reduction in insertion loss can be achieved in conjunction with a three fold increase in figure of merit ($°$/dB) compared to the case with direct metallization on the ferroelectric layer.

I. 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 may require thousands of phase shifters and hence some focus needs to be placed on exploring new and innovative designs for low cost and high performance microwave and millimeter wave phase shifters. Specifically, 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.

The proposed 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 a transmission line and, hence, in the design of low-cost phase shifters. $Ba_xSr_{1-x}TiO_3$ (BSTO) is commonly used, and recent advances in the development of these materials have resulted in lowering the dielectric constant ($\varepsilon_r \sim 100$), decreasing the loss tangent ($\tan \delta \sim 0.0009$), increasing the tunability ($\sim 20\%$), 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. Even with the implementation of the multi-dielectric layers designs in a microstrip transmission line arrangement [1], the resulting input impedance of microstrip and parallel plate type structures were unacceptably low.

A multilayer coplanar waveguide (CPW) with a thin low loss SiO_2 ($\varepsilon_r \sim 3.8$, $\tan \delta \sim$ 1e-4) layer separating the conductors from the ferroelectric material was developed in [2]. The simulation results showed an improvement in insertion loss of up to 5 dB in conjunction with an improvement in return loss of up to 15 dB at 10 GHz for the unbiased state ($\varepsilon_r \sim$

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723) compared to the direct metallization approach described in [3]. The multilayer design in [2] produced a figure of merit (FOM) of over 25 $^\circ$/dB at 10 GHz for line length of 10 mm, where FOM is defined as the amount of phase shift ($^\circ$) per decibel of insertion loss. The multilayer combination resulted in an overall reduced loss tangent without loss of tunability and phase shifting capabilities.

As may be expected, the inclusion of the multilayer dielectrics would complicate the implementation of the biasing circuit [2]. For the direct metallization approach the ferroelectric can be tuned using a simple bias tee arrangement. However, in the multilayer design the inclusion of the low-loss, low dielectric layer effectively "shorts out" the potential distribution and virtually eliminates the normal electric field component in the ferroelectric layer resulting in impractical biasing capabilities.

In this paper, we describe an alternative CPW phase shifter design approach that will enable biasing of the ferroelectric material using a simple bias tee. A via through the SiO_2 layer is employed to allow the conducting strip to contact the ferroelectric material without disrupting the crystal structure of the material. The signal conductor via approach is particularly well-suited in such applications due to its ease in fabrication and low cost design. The SiO_2 layer under the ground plane conductors maintains the overall low loss tangent without loss of tunability, input impedance, and FOM.

II. Simulated Models and Numerical Results

The multilayer CPW illustrated in Fig. 1 shows the cross section of the signal conductor in contact with the ferroelectric layer. For simulation purposes, WIPL-D [4] and LINPAR [5] were used to develop design curves for the aforementioned phase shifter.
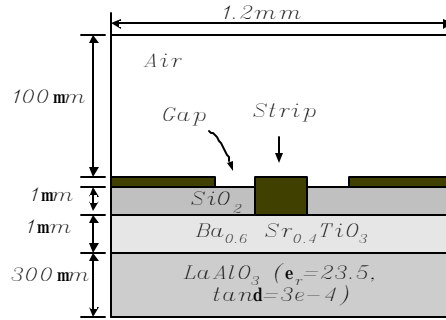

Fig. 1. Schematic of multilayer CPW where a via is formed in the SiO_2 (ε_r=3.8) layer to allow the conducting strip to contact the ferroelectric layer. The conductor thickness is 0.1 μm.

The characteristic impedance, attenuation, phase shift and FOM were simulated for the multilayer CPW at a frequency of 10 GHz for various strip widths and gap widths, exhibiting well-behaved design curves at this frequency. Fig. 2 depicts simulated data for the multilayer CPW with a dielectric constant of 700 (average between bias and unbiased states) and tan δ of 0.0075. Large strip and gap widths showed characteristics of high FOM, low attenuation, and 50 Ω characteristic impedance, and constitutes an improvement in attenuation of up to 0.7 dB/mm and a three fold improvement in FOM over the multilayer approach described in [3].

Increased phase shift may be realized by increasing the ferroelectric thickness; however, at the expense of increased attenuation. The 1μm BSTO and SiO$_2$ thicknesses were chosen based on the optimal tradeoff between phase shift and attenuation, or in other words for maximum FOM. The attenuation constant was further broken up into its associated dielectric and conductor losses (see Fig. 2c) where it was found that the conductor loss was the dominant contributor, and that minimal conductor losses may be achieved by increasing the signal conductor strip and gap widths. Furthermore, the conductor losses may be improved by increasing the conductor thickness.
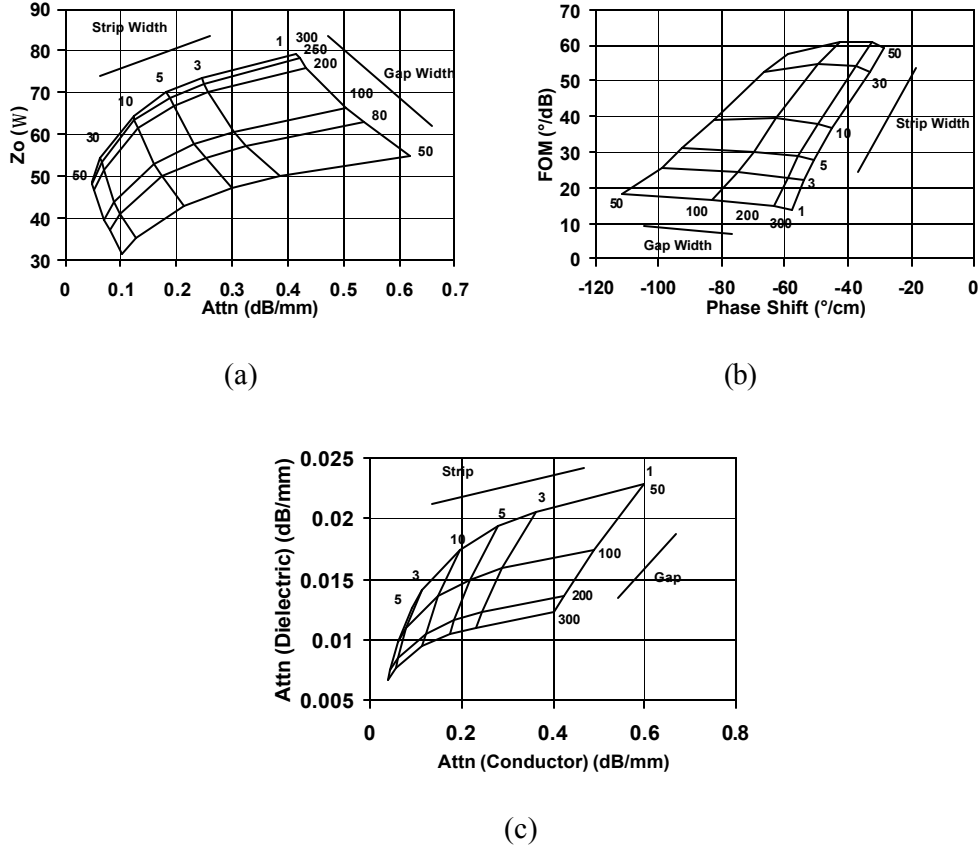

(a)

(b)

(c)

Fig. 2. (a) Impedance and attenuation, (b) FOM and phase shift, and (c) Dielectric and conductor attenuation at 10 GHz for various strip widths and gap widths, where SiO$_2$ = BSTO = 1um.

Theoretical normal electric field (E$_z$) distributions were simulated for the phase shifter depicted in Fig. 1 with a strip width of 20 μm and gap width of 100 μm at a frequency of 10 GHz, exhibiting consistent normal field components over the entire cross section of the BSTO layer. The field distributions near the edge of the conducting strip depend exclusively upon the width of the conducting strip in conjunction with the BSTO layer thickness. Adequate polarization of the BSTO material was achieved with larger strip widths and 1 μm thick BSTO layer. As discussed previously the dimensions required for enhanced RF performance is consistent with those required for sufficient ferroelectric biasing.

III. Conclusion

A novel, high performance, and low cost multilayer ferroelectric phase shifter design where a via was formed in the SiO_2 layer to allow the conducting strip to contact the ferroelectric layer for simple ferroelectric biasing was proposed and its performance was simulated and numerically evaluated. 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 insertion loss can be achieved (up to 0.7 dB/mm for unbiased case) and as high as three fold increase in the figure of merit (^{o}/dB) is possible compared with direct metallization approach. It was also found that the dimensions required for optimal RF performance is consistent with those required for sufficient ferroelectric biasing. This, in conjunction with the relative simplicity of the design and fabrication of the CPW phase shifter, makes it an ideal candidate for low-cost and high performance communication applications.

IV. References

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