FERROELECTRIC–FERRITE TUNABLE PHASE SHIFTERS

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Abstract — Coplanar waveguide transmission lines fabricated on tunable substrates are being developed for use as true time delay phase shifters. We have fabricated such devices on substrates composed of ferroelectric thin films as well as ferroelectric thin films overlaying ferrite films. These ferroelectric thin film CPW transmission lines have exhibited good tuning properties as evidenced by the differential phase shift while maintaining reasonable losses. The ferroelectric-ferrite structures exhibit tuning which is equally dependent on magnetic and electric field biasing.

I. INTRODUCTION

It has long been known that the electric field dependence of the dielectric constant of ferroelectric materials could be useful in making tunable microwave devices and circuits [1-3]. Recently, there has been considerable progress in developing the pulsed-laser deposition (PLD) technique to deposit ferroelectric thin films that have the necessary material and electronic properties for tunable microwave electronic components [4]. Optimizing deposition, annealing, and doping conditions has resulted in ferroelectric thin films which retain a large dependence of the susceptibility on the applied electric field with acceptably low losses. A promising application of this technology is in phased arrays where the advantages of a continuously variable, true-time-delay, broadband phase shifter would be attractive. Many recent attempts to realize ferroelectric thin-film based phase shifting devices have focused on narrower band applications [5]. For wide band applications, coplanar waveguide (CPW), as shown in Fig. 1 offers an attractive choice since the electric field orientation makes optimum use of the thin film.

Concepts employing both ferroelectric and ferrite materials are being developed in order to mitigate the deleterious effects of modifying the capacitance per unit length on the impedance match of the transmission line. The addition of a ferrite makes it possible to independently tune both the inductance per unit length and capacitance per unit length. In principle, this will permit tuning of the phase velocity while maintaining the transmission line characteristic impedance, Z_c. A diagram of such a structure is shown in Fig. 2. The geometry is, of course, not to scale. The length of the CPW is on the order of 1 cm and the gap widths vary from 5.5 to 26 μm, and the center strip width varies from 6.4 to 33 μm.

II. DEVICE FABRICATION

The PLD technique used for the formation $Ba_xSr_{1-x}TiO_3$ ferroelectric films has been described in prior work [6]–[8]. An excimer laser is used to vaporize material from a high-density sintered target of compressed powder, containing the stoichiometric ratios necessary for the desired film. A substrate, thermally sunk to a heated stainless steel stage, is placed in close proximity to the sintered target so that as the laser ablates material from the target, the plume of material created is deposited on the substrate. Material is deposited on the substrate at a rate of 2 Å per laser pulse.

For ferroelectric films deposited directly on single crystal dielectric substrates, such as MgO and $LaAlO_3$, the resulting film is single-phase and (100) oriented. Typical film thicknesses are 0.5-1.0 μm and film compositions are $Ba_{0.5}Sr_{0.5}TiO_3$ or $Ba_{0.6}Sr_{0.4}TiO_3$. For the experiments involving the integration of ferroelectrics with ferrites, the ferroelectric thin film is deposited on 100 μm-thick YIG grown on a GGG substrate by liquid phase epitaxy (LPE).

To minimize conductor losses, the CPW transmission lines are fabricated by photolithography and metal-liftoff patterning using a multi-level resist process. The desired pattern is first developed as windows in a tri-layer resist consisting of PMMA, a thin metal film, and Microposit 1818 photoresist. A mask with the desired pattern is used to expose and develop the 1818 resist. The pattern is transferred to the metal film by wet etching. The 1818 resist is removed by flood exposure and developing. After flood exposure by deep-UV to transfer the pattern, the PMMA is developed and the sample is ready for the final metallization. At this point, the substrate surface is exposed only where the desired metal electrode structure is needed. Silver is deposited in an e-beam evaporator over the entire substrate, to a thickness of at least 1.5 μm, followed by a thin gold layer which preserves the surface for electrical contact. Liftoff in acetone is used to delineate the final CPW pattern. This is the same metallization process that has been used to fabricate ferroelectric interdigitated varactors [9].

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Fig. 1 and Fig. 2, although not to scale, illustrate the CPW phase shifting structures which were fabricated for the ferroelectric thin film on single crystal dielectric substrate and the ferroelectric thin film on thick film YIG on GGG substrate, respectively. The epitaxial single crystal YIG film is grown by LPE.

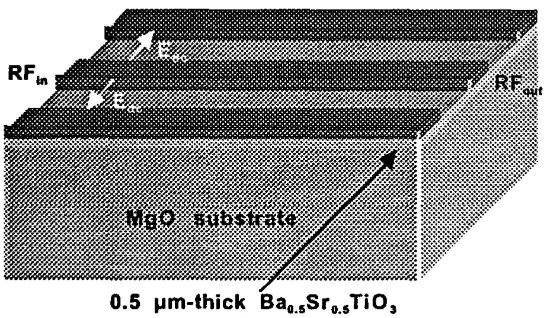

Fig. 1. Diagram of the ferroelectric thin film CPW structure. Bias is supplied to the center conductor. CPW lengths measured were 1.0 cm and 0.85 cm. Center strip widths varied from 6.4 to 33 µm. Gaps ranged from 5.5 µm to 26 µm.

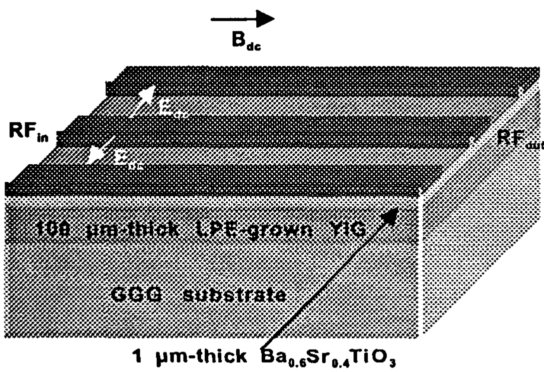

Fig. 2. Diagram of the structure measured. The length of the CPW section was 1 cm with 19 µm gaps and a 30 µm strip.

III. Measurements

Microwave *S*-parameter measurements of all devices are made over the 50 MHz to 20 GHz frequency range using an HP 8510C network analyzer. The DC electric field bias is applied between the center conductor and the outer conductors of the CPW using bias tees.

A. Ferroelectric Films on Dielectric Substrates

The devices are measured using ground-signal-ground Picoprobe microwave probes. Using the internal bias tees the device bias is set initially at -40 volts, and swept in 5-volt steps to +40 volts, and then back to -40 volts.

When external bias tee are used, measurements are made in the operating range (12 - 20 GHz) of the bias tees. With these higher voltage bias tees the voltage is applied in 25 V steps up to a maximum of 200 Volts. For the CPW structures we have fabricated to date, the largest electric field applied has been 273 KV/cm across a 5.5 µm gap which corresponded to an applied bias of 150 Volts.

B. Ferroelectric Films on Thick-Film YIG on GGG

The finished device is rigidly mounted in a test fixture and the CPW is wire bonded to SMA connectors. The completed assembly is inserted between the pole faces of an electromagnet. The pole faces are 10 cm in diameter and the separation between the pole faces is 7.5 cm. The center strip of the CPW is aligned with the axis of the magnet poles. The resulting electric and magnetic field orientations are shown in Figure 2. Microwave data are collected with a HP 8510C vector network analyzer. Electric field bias is applied utilizing the internal bias tees of the network analyzer test set.

IV. Results

A. Ferroelectric Films on Dielectric Substrates

Several ferroelectric thin-film CPW transmission lines have been tested. Good results have been obtained using both MgO and $LaAlO_3$ substrates. The results discussed below will focus on the results obtained with MgO substrates since the losses, particularly at higher frequencies, are less and the lower capacitance per unit length values are more suitable to realizing a 50 Ohm Z_c. As a result, the transmission lines fabricated on MgO are better suited to broadband device realization. The measured insertion loss and return loss for a 0.85 cm-long CPW using 26 µm gaps and 33 µm center strip is shown in Figure 3. The insertion loss increases to about 7.5 dB at 20 GHz. The bias dependence of the insertion loss is quite small for this device. Although the line is well matched at low bias, as the bias is increased the mismatch becomes apparent in the frequency dependence of the insertion loss. Obviously, in addition to modulating the phase velocity with the applied dc field, the Z_c of the structure is modulated proportionately.

The differential phase shift for this same device is shown in Figure 4. At 20 GHz the differential phase shift is greater than 30° for a bias of only 15 KV/cm. The change in Z_c as the bias is applied is obvious from the abrupt step-like structure in the differential phase shift which is particularly pronounced at the lower frequencies. This illustrates a difficulty in realizing broadband, continuously variable, true-time delay phase shifters. Tunable matching networks will be required to realize practical devices.

However, since transitions to more realistic CPW cross-sections will need to be incorporated in realistic devices it is quite reasonable that the ferroelectric material present will facilitate the realization of tunable matching to maintain a broadband match.

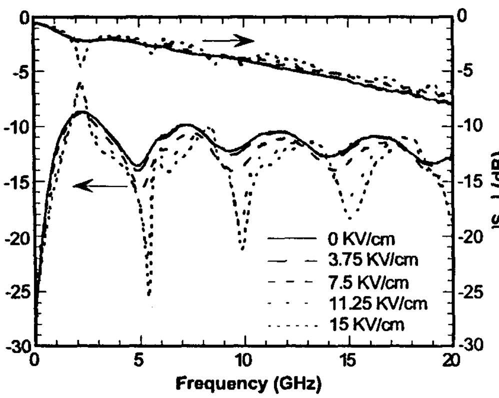

Fig. 3. Insertion and return loss versus for various electric field biases. The change in Z_c impedance is very apparent, as the electric field increases the match decreases. CPW was 0.85 cm-long with 26 m gaps and 33 m strip.

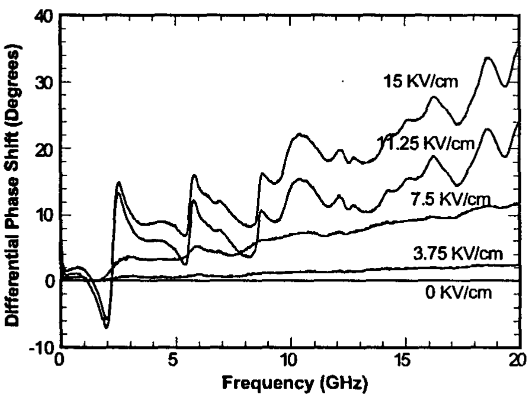

Fig. 4. Differential phase shift corresponding to the measurements in Figure 2. Very modest electric field intensities result in over 30 degrees of differential phase shift at 20 GHz.

The results discussed above are for a well matched device. Much larger differential phase shifts have been measured in ferroelectric thin-film CPW devices which were not well matched. For a low Z_c line with small gaps it is possible to bias to very high fields using external bias tees. The fields obtainable are nearly 20 times larger than those used to obtain the tuning shown in Figure 4. These bias tees only function above 12 GHz. However, at 20 GHz it has been possible, in a 1cm-long line, to obtain 120° of differential phase shift with an applied field of 272 KV/cm.

B. Ferroelectric Films on Thick-Film YIG on GGG

Figure 5 shows the S_{11} and S_{21} for the CPW transmission line shown in Fig. 2. The interaction of the propagating microwave signal and the YIG is evident by the presence of the resonance at 2.5 GHz. This resonance shifts with magnetic field to 3.8 GHz, and demonstrates that the basic magnetic properties of the ferrite are unaffected by the deposition of the ferroelectric BST and the subsequent device processing. In the 10 to 14 GHz frequency range, the transmission line exhibits a 6.5 dB insertion loss and a 10 dB or better return loss. The impedance match to the 50 Ohm test environment is not optimal. This is due in large part to the fact that the permittivity of the BST is difficult to predict and control, especially the immature nature of the material technology with respect to deposition of BST on YIG. Adjusting the physical dimensions of the CPW can correct for most of this mismatch, and efforts are presently underway adjust the geometry accordingly.

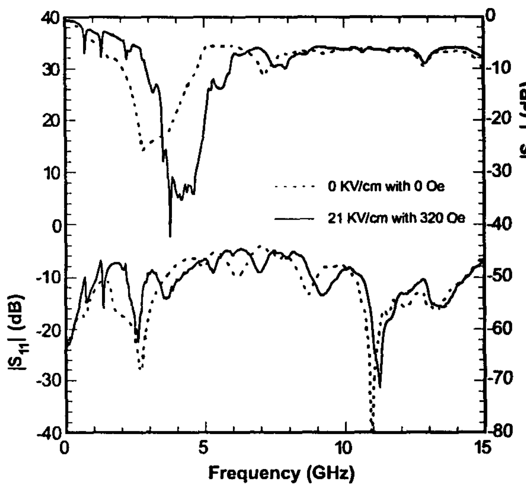

Fig. 5. Measured insertion loss and return loss for the CPW fabricated on the sample consisting of a ferroelectric thin film on thick-film YIG.

Figure 6 demonstrates the effects of both electric field and magnetic field on the differential phase shift of the line in the frequency range from 10 to 12 GHz. At a frequency of 11.6 GHz, electric field variation from 0 to 21 kV/cm results in a phase shift of 20 degrees. Magnetic field variation from 0 to 320 Oersteads results in a phase shift of around 18 degrees. Applied together, both magnetic and electric field biases produce an observed phase shift of 42 degrees. The effect of simultaneous electric and magnetic field biasing on the propagating microwave radiation is complicated due to the different spatial regions occupied by ferroelectric and ferrite materials and the difference in overlap of these regions with the microwave fields. Yet, it can be noted to first order that superposition seems to apply with respect to the additive nature of the differential phase shift components via the two different tuning mechanisms.

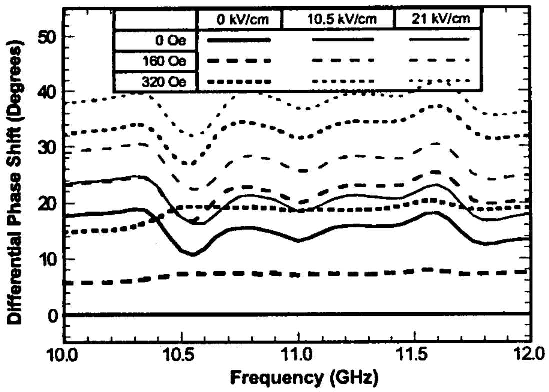

Fig. 6. Differential phase shift versus frequency for several electric and magnetic field biases. The total differential phase shift is nearly equal to the sum of the electric field only and magnetic field only phase shifts.

V. Conclusion

CPW transmission lines have been fabricated from ferroelectric thin films of $Ba_xSr_{1-x}TiO_3$ on MgO and $LaAlO_3$ substrates, which can produce reasonable differential phase shifts and which have losses that are sufficiently low for microwave circuit applications. The advantage of the CPW approach is that truly broadband devices are possible once tunable matching networks are incorporated into the design. The maximum differential phase shift observed at 20 GHz was 120° from a poorly matched structure. At much lower bias levels 30° of differential phase shift was observed at 20 GHz from a well-matched device with approximately 7.5 dB of insertion loss. This bias level, limited by the bias tees employed, constrained the applied bias field to approximately 5% of the value which has been successfully applied to these materials. Conservative extrapolation would indicate that 360° of differential phase shift could be obtained from this device for 7.5 dB of insertion loss at 20 GHz since the loss is only minimally dependent on bias.

In addition, CPW transmission lines have been fabricated using ferroelectric $Ba_xSr_{1-x}TiO_3$ deposited on YIG. Initial microwave measurements have indicated that both magnetic and electric tuning mechanisms are active and that the phase velocity can be tuned equally well by either magnetic or electric field. An equivalent differential phase shift can be achieved with a magnetic bias on the order of 320 Oersteds as has been achieved with an electric field bias of 21 kV/cm. The effects are additive to first order, allowing for maximum observed total differential phase shift of over 40 degrees at 11.6 GHz.

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References

[1] V. K. Varadan, D. K. Gohdgaonkar, V. V. Varadan, J. F. Kelly, and P. Glikerdas, "Ceramic phase shifters for electronically steerable antenna systems", *Microwave Journal*, vol. 35, no. 1, pp. 116-127, Jan. 1992.

[2] V. Chivukula, J. Ilowski, I. Emesh, D. McDonald, P. Leung, and M. Sayer, "Dielectric properties of ferroelectric thin films in the frequency range of MHz-GHz", *Integr. Ferroelectr.*, vol. 10, no. 1-4, pp. 247-255, March 1996.

[3] A. Outzourhit, J. U. Trefny, T. Kito, B. Yarar, A. Naziripour, and A. M. Hermann, " Fabrication and characterization of $Ba_{1-x}Sr_xTiO_3$ tunable thin film capacitors", *Thin Solid Films*, vol. 259, no. 2, pp. 218-224, April 1995.

[4] J. S. Horwitz, D. B. Chrisey, J. M. Pond, R. C. Y. Auyeung, C. M. Cotell, K. S. Grabowski, P. C. Dorsey, and M. S. Kluskens, "$Sr_xBa_{1-x}TiO_3$ thin films for active microwave device applications", *Integr. Ferroelectr.*, vol. 8, no. 1-2, pp. 53-64, 1995.

[5] F. W. Van Keuls, C. H. Mueller, F. A. Miranda, R. R. Romanofsky, C. L. Canedy, S. Aggarwal, T. Venkatesan, R. Ramesh, J. Horwitz, W. Chang, and W.J. Kim, "Room temperature thin film $Ba_xSr_{1-x}TiO_3$ Ku-band coupled microstrip phase shifters: effects of film thickness, doping, annnealing and substrate choice," *1999 IEEE MTT-S International Microwave Symp. Dig*, vol. 2, pp. 737-740, June 1999.

[6] K. S. Grabowski, J. S. Horwitz, and D. B. Chrisey, "Pulsed laser deposition of oriented $PbZr_{.55}Ti_{.45}O_3$", *Ferroelectrics*, vol. 116, no. 1-2, pp. 19-33, 1991.

[7] J. S. Horwitz, D. B. Chrisey, K. S. Grabowski, and P. E. Leuchtner, "Pulsed laser deposition of electronic ceramics", *Surf. Coat. and Technol.*, vol. 51, no. 1-3, pp. 290-298, April 1992.

[8] L. A. Knauss, J. S. Horwitz, D. B. Chrisey, J. M. Pond, K. S. Grabowski, S. B. Qadri, E. P. Donovan, and C. H. Mueller, "Dielectric susceptibility and strain $Sr_{1-x}Ba_xTiO_3$ ferroelectric thin films grown by pulsed laser deposition", *Mater. Res. Soc. Symp. Proc.*, vol. 388, pp. 73-78, April 1995.

[9] S. W. Kirchoefer, J. M. Pond, A. C. Carter, W. Chang, K. K. Agarwal, J. S. Horwitz, and D. B. Chrisey, "Microwave properties of $Sr_{0.5}Ba_{0.5}TiO_3$ thin-film interdigitated capacitors," *Microwave and Optical Technology Letters*, vol 18, no. 3, pp. 168-171, May 1998.