Ferroelectric Thin Films on Ferrites for Tunable Microwave Device Applications

J. M. Pond, S. W. Kirchoefer. H. S. Newman, W. J. Kim, W. Chang, and J. S. Horwitz
Naval Research Laboratory
4555 Overlook Ave., S. W., Washington, DC, USA

Abstract — Wideband tunable microwave transmission lines are being developed using pulsed-laser-deposited ferroelectric thin films on liquid-phase-epitaxially grown ferrite thick films. The ferroelectric-ferrite combination makes it possible to independently tune both the inductance per unit length and capacitance per unit length of the integrated structure, and thus, overcome the deleterious effects of modifying the capacitance per unit length on the impedance match of the transmission line. Initial microwave measurements have indicated that both magnetic and electric tuning mechanisms are functional 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 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.

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. Interdigitated capacitors have been used to correlate microwave properties of the ferroelectric film with the PLD deposition conditions [5].

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 [6]. For wide band applications, coplanar waveguide (CPW) offers an attractive choice since the electric field orientation makes optimum use of the thin film.

The combination of ferroelectrics with ferrites is being pursued to mitigate the deleterious effects of modifying the capacitance per unit length on the impedance match of the transmission line. The phase velocity of a transmission line is given by

$$v_p = \sqrt{\frac{1}{LC}} \qquad (1)$$

while the characteristic impedance is given by

$$Z_c = \sqrt{\frac{L}{C}} \qquad (2)$$

where L is the inductance per unit length and C is the capacitance per unit length. While the use of ferroelectrics yields a transmission line with a voltage dependent phase velocity it results in the characteristic impedance being detuned from its optimum value. The addition of a ferrite makes it possible to independently tune both the inductance per unit length with a magnetic field and the capacitance per unit length with an electric field. In principle, this will permit tuning of the phase velocity while maintaining the transmission line characteristic impedance. A diagram of such a structure is shown in Fig. 2. The length of the CPW is on the order of 1 cm and the gap widths used vary from 5 to 26 μm, and the center strip width used varies from 6 to 33 μm.

DEVICE FABRICATION

The PLD technique used to grow the $Ba_xSr_{1-x}TiO_3$ ferroelectric films has been described in prior work [7, 8]. An excimer laser is used to vaporize material from a high-density sintered target of compressed powder that contains 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 the experiments involving the integration of ferroelectrics with ferrites, the ferroelectric thin film is deposited on a 100 μm-thick yttrium iron garnet (YIG) film grown on a gadolinium gallium garnet (GGG) substrate by liquid phase epitaxy (LPE). Typical film thicknesses are 0.5-1.0 μm and film compositions are $Ba_{0.5}Sr_{0.5}TiO_3$ or $Ba_{0.6}Sr_{0.4}TiO_3$.

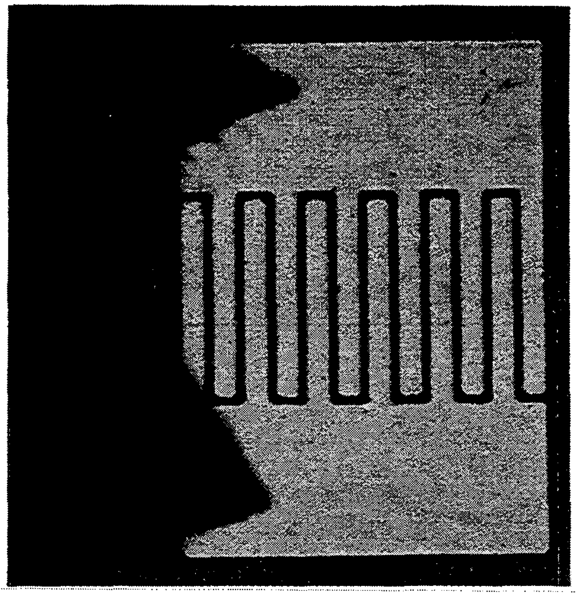

Fig. 1. Photography of an interdigitated capacitor with microwave probe in contact. The total length of the device is 250 μm and the interdigital spacing is nominally 6 μm.

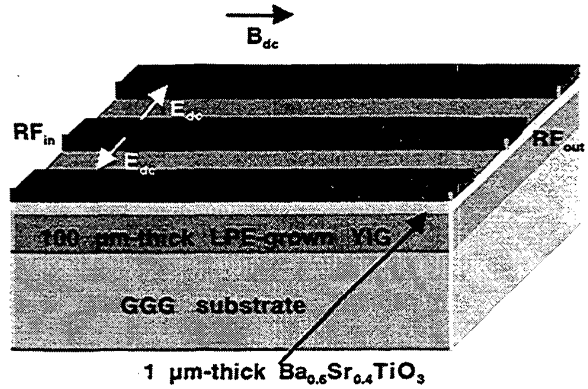

Fig. 2. Diagram of the structure measured. The length of the CPW section was 1 cm with 19 μm gaps and a 30 μm strip.

To minimize conductor losses, the interdigitated capacitors and CPW transmission lines are fabricated by photolithography and metal-liftoff patterning [9]. 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. The substrate surface is exposed only where the desired metal electrode structure is needed. Silver is e-beam evaporated over the entire substrate, to a thickness of at least 1.5 μm, followed by a thin gold layer to preserve the quality of the contact. Liftoff in acetone is used to delineate the final pattern.

Although the yield is very high for the interdigitated capacitors, yield for CPW lines is about 50%. This is due to the difficulty in obtaining consistent patterning linewidths and metal film liftoff for 10-μm wide windows over the 1 cm length of the transmission line. Separate patterning of the ground plane metallization and center strip has been attempted as a means of improving yield. Although yields were improved at the initial step of patterning the ground plane, the complication of alignment and liftoff of the center strip ultimately resulted in no yield improvement over patterning the structure in a single step.

Fig. 2, although not to scale, illustrates the CPW transmission lines which were fabricated. Best results to date were obtained using a 30 μm wide center strip with 19 μm gaps between the center conductor and outer conductors (ground).

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 using the internal bias tees of the network analyzer.

Interdigitated Capacitors

Interdigitated capacitors, consisting of 6 finger pairs with 80 μm long fingers separated by 6 μm wide gaps, are used to characterize the electrical properties of the ferroelectric thin film. Using the internal bias tees of the network analyzer the device bias is set initially at -40 volts, and swept in 5-volt steps to +40 volts, and then back to -40 volts. This voltage limit is determined by the internal bias tees of the network analyzer test set, and not by any intrinsic breakdown limit of the films. The devices are contacted by means of signal-ground Picoprobe microwave probes. Microwave reflection data (S_{11}) is collected digitally and stored on a personal computer.

Coplanar Waveguide Transmission Lines

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 Fig. 2.

RESULTS

Interdigitated Capacitors

Using a parallel combination of a resistor and capacitor as an equivalent circuit, the device capacitance and quality factor (Q) are calculated from the S_{11} data. The capacitance and Q are displayed in Figs. 3 and 4 for a device fabricated on a 0.5 μm thick $Ba_{0.5}Sr_{0.5}TiO_3$ film deposited on a 100 μm YIG film on a GGG substrate.

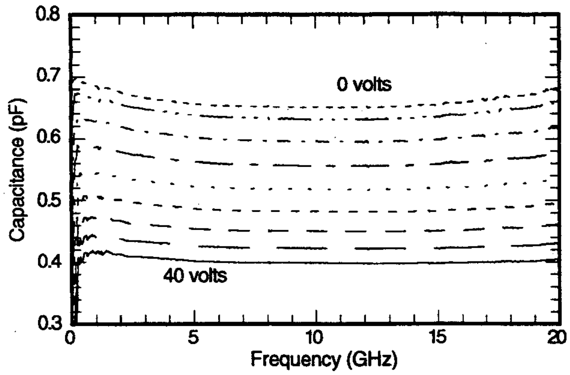

Fig. 3. Capacitance versus frequency for several bias voltages of the interdigitated capacitor. Capacitance is determined from S_{11} assuming a parallel RC model.

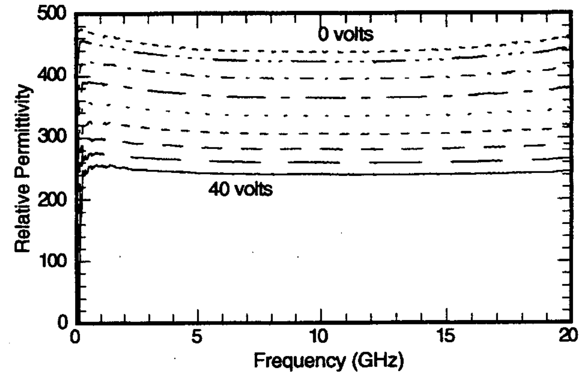

Fig. 5. Relative permittivity, as determined from the measured microwave response, versus frequency for several bias voltages of the interdigitated capacitor.

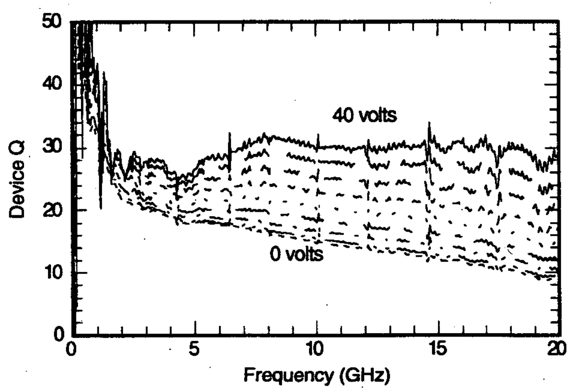

Fig. 4. Device Quality Factor versus frequency for several bias voltages of the interdigitated capacitor. Capacitance is determined from S_{11} assuming a parallel RC model.

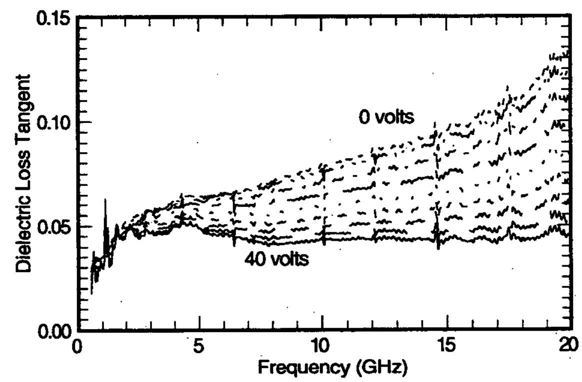

Fig. 6. Dielectric loss tangent, as determined from the measured microwave response, versus frequency for several bias voltages of the interdigitated capacitor.

At 10 GHz this device shows capacitance tuning from 0.65 pF to 0.40 pF in the range from 0 to 40 volts, while the device Q varies from 15 to 30. This represents 40% tuning with an average Q of 23. Relative dielectric constant, ε_r, and loss tangent, tanδ, can be estimated since the thickness of the YIG film is large compared to the BST thickness and the gap width.

Using a conformal mapping, partial capacitance technique similar to that of Gevorgian [10], the extracted ε_r and tanδ are displayed in Figs. 5 and 6. These results show that these BST films deposited on YIG are of comparable quality to the state-of-the-art for BST on MgO. The fractional change in relative permittivity with bias is larger than the fractional change in device capacitance since the substrate and air contribute to the device capacitance and are in parallel with the ferroelectric capacitance. Similarly, the tanδ of the ferroelectric film is larger than the reciprocal of the device Q.

Coplanar Waveguide Transmission Lines

Fig. 7 shows the magnitude of the microwave scattering parameters, S_{11} and S_{21}, for the CPW transmission line shown in Fig. 2. S_{11} and S_{21} are the reflected and transmitted signals, respectively.

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, as expected, the basic magnetic properties of the ferrite are unaffected. 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 a 50 Ohm system is not optimal due, in large part, to the difficulty in realizing the precise value required for the relative permittivity of the BST on YIG.

Fig. 8 demonstrates the effects of both electric field and magnetic field on the differential phase shift from 10 to 12 GHz. At 11.6 GHz, an electric field variation from 0 to 21 kV/cm results in a phase shift of 20 degrees. A magnetic field variation from 0 to 320 Oersteds results in a phase shift of about 18 degrees. Applied together, these magnetic and electric field biases produce a phase shift of 42 degrees. The effect of simultaneous electric and magnetic field biasing on the propagating microwave signal is complicated due to the different spatial regions occupied by ferroelectric and ferrite and the difference in overlap of these regions with the microwave fields. However, to first order, superposition applies with respect to the additive nature of the differential phase shift components via the two different tuning mechanisms.

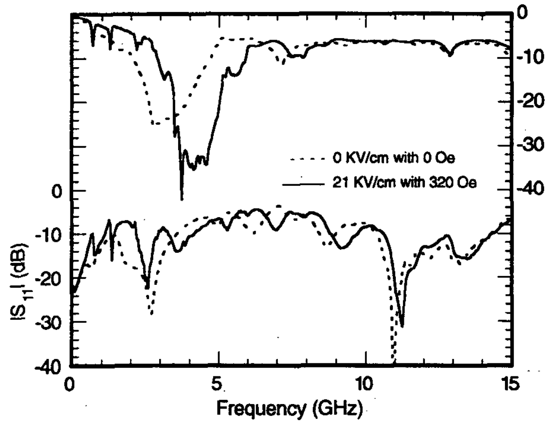

Fig. 7. Measured insertion loss ($|S_{21}|$) and return loss ($|S_{11}|$) for the CPW fabricated on the sample consisting of a ferroelectric thin film on thick-film YIG.

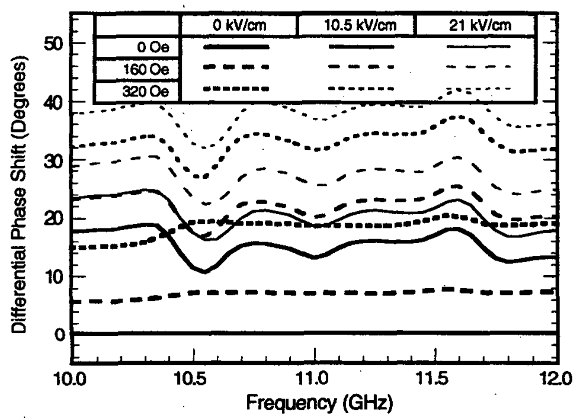

Fig. 8. Differential phase shift versus frequency for several electric and magnetic field biases. The total differential phase shift is nearly equal to the sum of the electric field only and magnetic field only phase shifts.

CONCLUSION

It has been demonstrated that PLD can be used to deposit high quality ferroelectric thin films on single crystal YIG. Microwave reflection measurements of interdigitated capacitors fabricated on these BST films have resulted in devices that exhibit tuning as high as 40% with average Q values of 25. This compares favorably with good quality BST on MgO, and should result in transmission lines with phase shift contributions of the ferroelectric tuning that equals that of phase shifters fabricated without ferrites.

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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