Compact Ferroelectric Reflection Phase Shifters at X-Band

Justin L. Serraiocco, Peter J. Hansen*, Troy R. Taylor*, James S. Speck*, and Robert A. York

Electrical and Computer Engineering Dept, University of California, Santa Barbara, CA, 93106, USA
(* Materials Dept.)

***Abstract* — Compact reflection phase shifters using thin film barium strontium titante have been developed. X-band designs measuring less than 0.5 mm^2 are realized by using only lumped element components. The circuits are constructed monolithically, using planar spiral inductors, thin-film resistors, and parallel plate ferroelectric capacitors on a dielectric substrate. A novel low impedance transforming design is used to enhance performance. The first prototypes show promise, giving approximately 14°/dB. Further process and design improvements will increase performance.**

I. Introduction

Ferroelectric thin films are a promising technology to reduce the cost of microwave phase shifters. The voltage tunable dielectric constant of ferroelectrics such as barium strontium titanate (BST) can also be used in a number of other circuits, including frequency tunable filters and matching networks. When the BST is utilized in thin film parallel plate capacitors, low voltage operation and integration with other passive components can be achieved.

A number of papers have been published recently on ferroelectric phase shifters. In [1], a 180° distributed transmission line phase shifter was presented. The circuit exhibited 87°/dB figure of merit at 8.5 GHz. In [2], a 90° reflection phase shifter with a 89°/dB figure of merit at 1.87 GHz was presented. Both circuits demonstrate very competitive performance but have rather large physical dimensions. Each measures over 50 mm^2. In this paper, we present a compact monolithically constructed reflection phase shifter using spiral inductors, thin-film resistors, and parallel plate ferroelectric capacitors. The design is similar to that shown in GaAs MMIC technology in [4]. The design is improved for ferroelectric technology by using an integral impedance transformer. At X-band, circuits smaller than 0.5 mm^2 can be constructed.

II. Circuit Design

The reflection phase shifter (RPS) operates by reflecting the input signal off a tunable reactive load. The tuning of the load results in a variable phase shift. To create a two-port device with isolated input and output ports, identical reactive loads are connected to the thru and coupled ports of a hybrid coupler. Although the signals at these ports are in quadrature, upon reflection from the reactive loads they will recombine in phase at the hybrid's isolated port.

The tunable reactive load can be realized by a shunt ferroelectric capacitor. This is the simplest approach, but it offers limited phase shift tuning. Resonating the ferroelectric capacitor with a series inductor increases the phase shift tuning range. The equation for maximum differential phase shift is given in [4] as:

$$\Delta\phi = 4\arctan\left(\frac{Z_{Cv0}}{Z_0}\frac{1}{2}\left(\sqrt{r_C}-\frac{1}{\sqrt{r_C}}\right)\right)$$

where r_C is the capacitance tuning ratio. Z_{Cv0} is the reactance at the center value of the variable capacitor, and is defined by:

$$Z_{Cv0} = \frac{1}{\omega_0 C_{v0}}$$

and the corresponding inductance is:

$$L_l = \frac{Z_{Cv0}}{2\omega_0}\left(\sqrt{r_C}+\frac{1}{\sqrt{r_C}}\right).$$

If a large differential phase shift $\Delta\phi$ is desired, a relatively large inductance and small tunable capacitance result. When the tuning ratio r_C is limited, the required inductance increases, while the necessary capacitance decreases. The limited tuning ratio of BST (approximately 2.5:1) results in element values that are fairly extreme at higher frequencies.

Large valued spiral inductors have significant parasitics that give them low self-resonant frequencies. The large dielectric constant of ferroelectric material results in high capacitance densities, which in turn results in small electrode areas. The BST used here had a density of approximately 15fF/um^2. Small capacitors have parasitics that can reduce the tuning range of the device below that of the material. These restrictions can limit the

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achievable phase shift to values below that attainable at lower frequencies.

The approach suggested here is to change the characteristic impedance Z_0 in the equations to a smaller value. The result is a smaller inductance and a larger capacitance compared to higher values of Z_0. Smaller inductors have fewer parasitics and higher self-resonant frequencies. The impact of parasitics on larger tunable capacitors is reduced, resulting in higher tunabilities.

Normally, changing the characteristic impedance of a circuit is not a feasible approach. However, the reactive loads are connected to the external world through a hybrid coupler. It is possible to maintain the input and isolated (output) ports of the hybrid at the standard characteristic impedance of the external circuit while varying impedance of the thru and coupled ones [3].

The combination of a lumped element hybrid coupler and a lumped series LC resonator load can give phase shifters that consume very little substrate area, as first demonstrated in [4]. The design can potentially be extended to higher frequencies and larger phase shift ranges by varying the characteristic impedance of the circuitry internal to the device. The approach also allows technologies with limited capacitor tunabilities to achieve higher performance than would be possible with a fixed impedance design. Additional benefits include smaller circuit areas and lower losses from the reduced size of the load inductors.

III. Circuit Implementation

The circuits were built on sapphire substrates. The ferroelectric thin film, $Ba_{0.5}Sr_{0.5}TiO_3$, was deposited by RF magnetron sputtering onto a platinum bottom electrode. The films had a thickness of 250 nm, and had a voltage tuning range of 10 V. The platinum top electrode was then deposited, and the remainder of the BST was etched from the substrate. Nichrome for the biasing resistors was deposited. One micron of gold was evaporated to form the spiral inductors. Air-bridges for the inductors were formed using an additional 0.5 um of gold.

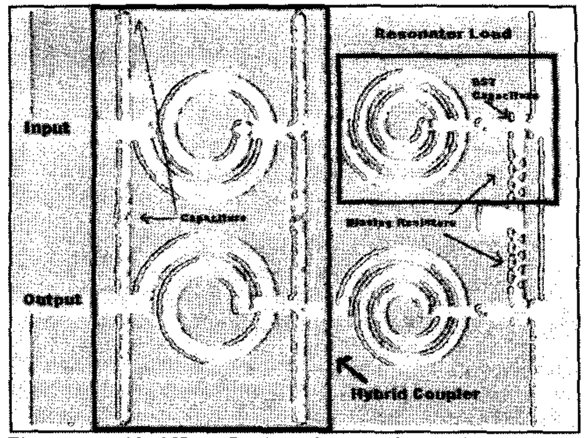

Fig. 1. A 10 GHz reflection phase shifter. The input and output ports are to the left of the spirals. The reactive loads are at the right of the picture. The circuit measures about 0.7 mm on each side and consumes under 0.5 mm^2.

The circuits were connected to short sections of coplanar waveguide for testing with Cascade wafer probes. The voltage biasing was achieved by contacting the circuits with a needle probe.

IV. Results

Two circuit designs were implemented and tested. The circuits were both designed for operation at 10 GHz. The first design used a hybrid with 50Ω characteristic impedances and a 180° reactive load. The hybrid included two spiral inductors and 6 ferroelectric capacitors. These small valued capacitors were not tuned, and could have been implemented with a conventional dielectric. The reactive load was implemented with a 1.86 nH inductor and a 0.24 pF capacitor. With tuning, this capacitance would decrease in value to 0.1 pF.

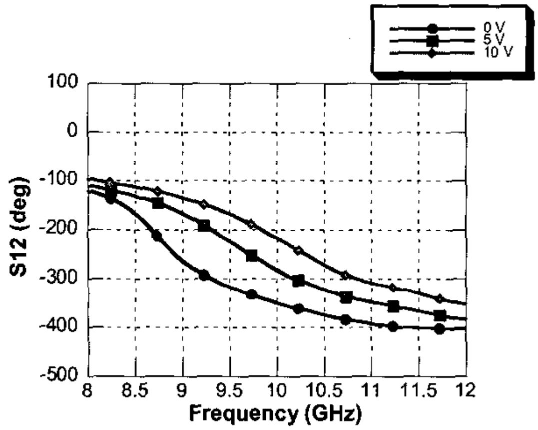

Fig. 2. The full 180° phase shift of the first design was not achieved. At 9.4 GHz, 148° of phase shift was recorded.

The second circuit utilized a hybrid with a thru and coupled port impedance of 25 Ω. This impedance is internal to the phase shifter; the input and output ports of the overall device remain at 50 Ω. This was connected to a 90° reactive load consisting of a 0.38 nH inductor and 1.15 pF capacitor. The impact of changing the internal impedance on the component values is shown in Table 1. The inductors and capacitors are much more realizable than in the fixed impedance case. Fabrication difficulties presently prevent direct comparisons of identical phase shifting circuits. The impedance-reduced hybrid has the same general form as the regular one, with two of the capacitors to ground removed.

Internal Z_0 (Ω)	$\Delta\phi$ (deg)	L (nH)	C (pF)
50	90	0.77	0.57
25	90	0.38	1.15
50	180	1.86	0.24
25	180	0.93	0.48

Table 1. It can be seen that for the same phase shift, the inductance values are significantly smaller for the lower internal impedance design. The capacitance required is larger, but this is beneficial in ferroelectric technologies with their high capacitance density.

The 180° design achieved a maximum phase shift of 148° at 9.4 GHz (Fig. 2). The center frequency was expected to be off somewhat due to the limited accuracy of closed form spiral inductor models. The limited tuning range of the BST capacitor prevented the full phase shift range from being achieved.

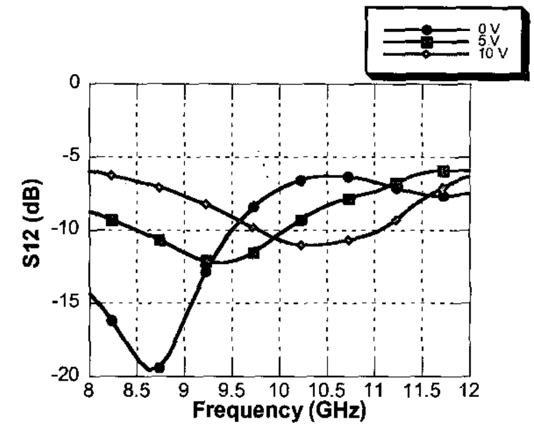

Fig. 3. The 180° RPS also suffers from high losses. The best performance achieved was –7.5dB at 11.5 GHz.

The large losses of the 180° design (Fig. 3) can be attributed to ohmic losses in the spiral inductors and dielectric losses in the capacitors. The relatively thin metal traces forming the spiral results in a large resistive component to the inductors. Commercial foundries often use metal thickness upwards of 3 microns to reduce these losses. The large number of ferroelectric capacitors (8 in total, although only 2 were used for tuning) also contributes significant losses. A high quality SiN dielectric layer could mitigate some of these losses.

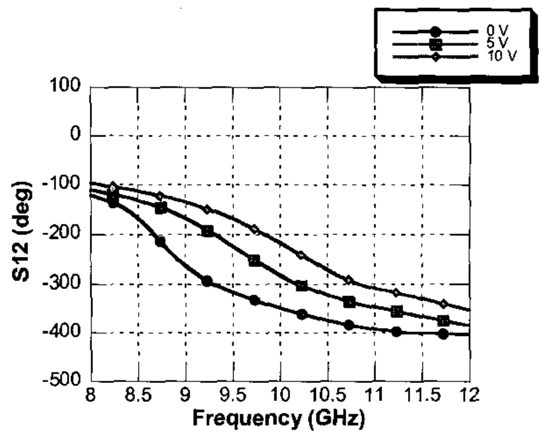

Fig. 4. The 90° RPS achieved a maximum of 82° phase shift at 8.3 GHz.

The impedance transforming phase shifter also did not achieve its full phase shifting range (Fig. 4) for the same reasons as mentioned before. The losses were reduced compared to the 180° design (Fig. 5) because of the reduced number of capacitors and smaller load inductor.

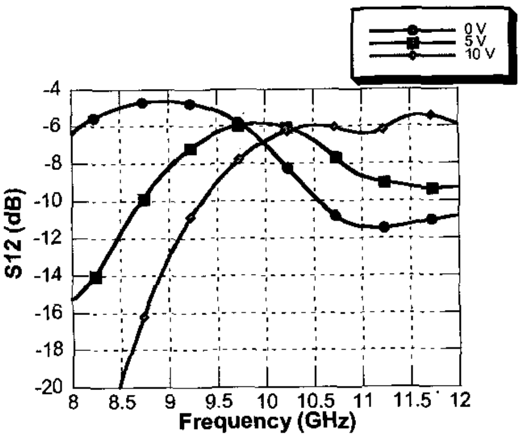

Fig. 5. The 90° RPS losses were slightly less than 180° design. At 10 GHz, the losses averaged –6.7 dB.

V. CONCLUSION

Two compact reflection phase shifter designs have been presented. These designs are significantly smaller than previous ferroelectric phase shifter designs. An impedance transforming circuit that eases lumped component realization was demonstrated. Both designs measure smaller than 0.5 mm^2, and give approximately 14°/dB performance. This figure of merit is a preliminary result, and should improve with further process refinements. Enhanced modeling of the circuit through EM simulations should further improve the performance.

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