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Cost Effective Ferroelectric Thick Film Phase Shifter Based on Screen-Printing Technology

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***Abstract* — A cost effective phase shifter technology based on ferroelectric thick film fabricated by screen-printing technology is described in this paper. As the demonstration device, a reflection-type phase shifter is designed and fabricated. At 2.2GHz to 2.6GHz band, the refection-type phase shifter offers an average differential phase shift about 48^o with a mean insertion loss of -2.4dB. The biasing DC voltage to achieve this performance is about 100V. This is the first report on screen-printed ferroelectric thick film phase shifter which offers promising device performance.**

***Index Terms* — Phase Shifter, ferroelectric, thick film, tunable, ceramic.**

I. INTRODUCTION

The key essential component of an electrically scanned arrays(ESAs) is the phase shifter. Critical phase shifter parameters such as the phase agility, RF insertion loss, switching times, power handling capability, sensitivity to variation of environment temperature depends seriously on the material and fabrication technology. Due to large amount of phase shifters that will be needed in ESAs for future communication and radar systems, it is important for a competitive phase shifter technology to be cost effective and offer high yield for industry production.

Table 1 summaries the four candidates of phase shifter technology. Ferrite devices and MEMs switches offer low RF insertion loss, but they are only suitable for application in which very high tuning speed is low. Further, the former is suitable for applications in which high power handling capacity is demanded and the later could be used in satellite communication where light and compact device is crucial. MMIC field effective transistor(FET) phase shifters[1] and ferroelectric phase shifters[2] are normally very lossy. But they can be switched or tuned very fast. Semiconductor FET can be monolithically on-chip integrated with power components(low noise amplifiers), which could compensate the high insertion loss. MMIC T/R modules[3] based on GaAs technology is actually one of the most successfully developed integration schemes for industryn. But the costs of semiconductor MMIC module is still too high to be widely employed in cost effective communication system.[3]

Phase shifters based on ferroelectric material is an alternative approach to implement cost effective ESAs. As presented in Table 1, the reported performance of ferroelectric thin film phase shifters is at the same level as FET phase shifters[4],[5]. There is even some efforts on replacing the semiconductor FET phase shifters with ferroelectric thin film phase shifters in T/R modules.[6] But both FET phase shifters and ferroelectric thin film phase shifters are based on epitaxial thin film technology. The necessary fabrication procedure including vacuum film deposition and high resolution patterning process make the device relatively high cost. To improve on the effective use of substrate with limited area, MMIC technology using lumped element design is necessary. In this case, the circuit design sacrifices the loss performance, because normally very narrow conducting line will be employed and this will produce high current density, which yields high microwave insertion loss. An alternative approach to all the above is the use of BSTO material which can be made in the form of thick film or thin sheets. Fortunately, ferroelectric material such as BSTO is a ceramic oxides and it is possible to be fabricated by LTCC[7] or HTCC [8] technology. Tape casting[8] or screen-printing technology[9] can be employed to form the designed in-plane shape of BSTO layer. In the system-on-package integration scheme of multilayer ceramic devices, BSTO material could be monolithically fabricated and the active components such as LNA can be mounted on board. The usual limit of substrate size will be largely alleviated and the fabrication of devices on a large area substrate is easier because of the printing approach, as opposed to the in-situ vacuum deposition of film. Further, distributed design of passive circuit could be employed via the 3-D implementation of multiplayer ceramic technology. We have reported the initial result of a reflective LC circuit employing a BSTO thick film tunable capacitor[9]. With DC biasing voltage of 100V, it offers a figure of merit(FOM) of 54^o/dB at 2GHz. This result is comparable to it of a previously reported BSTO thin film reflective circuits which offers a FOM about 60^o/dB.[10]

In this paper, a reflection-type phase shifter(RTPS) based on BSTO thick film fabricated by standard screen-printing technology is presented. The purpose of this work is to explore the integration scheme of ferroelectric thick film and other ceramic microwave dielectric material such as Al_2O_3. The device is designed to work at 2.4GHz. At the frequency range from 2.2GHz to 2.6GHz, the microwave measurement result illustrates quite promising differential phase shifting and loss performance with reasonable DC biasing voltage of 100V.

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TABLE 1.
COMPARISON OF DIFFERENT MICROWAVE PHASE SHIFTER TECHNOLOGIES.

	Semiconductor MMIC	Ferrite	Ferroelectric		MEMs Switches
			Thin Film (MMIC)	Thick Layer	
Insertion loss/ Phase shift	High (4-9dB/360^o)[1]	Low <1dB/360^o[1]	High (4-6dB/360^o)[2]	High >4dB/360^o	Low (<1dB/360^o)
Tuning speed	Fast(50-200ns)	Low(μs)	Fast(20ns)	---	Low(10μs)
Power handling Capacity	2 Watts	10W to 100W	1 W	---	1 Watt
Temperature Sensitivity	Low	Low to High	Acceptable	---	High
Drive Power	500mW	100mW to 2W	Negligible	negligible	Low
Size	Small	Large	Small	Medium	Small
Cost effective?	Expensive	Expensive	Medium	Low cost	Expensive
Highly integrated T/R module?	MMIC	Discrete device	Possible via (Flip-chip)[6]	Easy with LTCC	Via Surface Micromaching
Application	Fast tuning	High RF power	Fast tuning	Fast tuning Low cost	Satellite communication

II. MODELING AND DESIGN

The phase shifter is diagrammatically shown in figure 1. A one section 3-dB branch line coupler is used as the 90^o hybrid. The single resonant termination circuit is composed of the transformer(Lt), tunable capacitor(C) and the short to ground stub(Ls). All the transmission lines are designed in microstrip and are normalized to 50ohms; which is the characteristic impedance of the input and output lines. The substrate is Al_2O_3 ceramic with a thickness of 1mm. As mentioned above, the low price substrate makes it acceptable for distributed circuit design which could theoretically offer better loss performance than the lumped inductor design in highly integrated MMIC. The final packaged device is 25mmx15mmx1mm. The size of the device could be greatly reduced if 3-D design technology is employed.

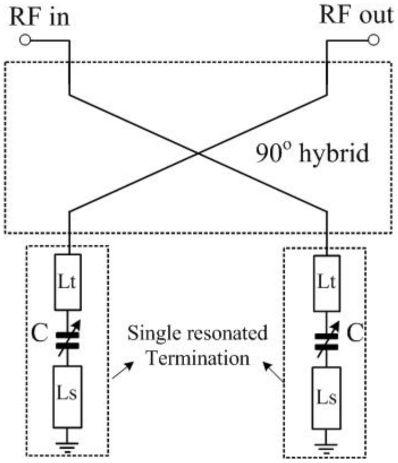

Figure 1. Schematic diagram of the RTPS equivalent circuit.

According to the circuit theory of RTPS, with ideal 90^o lossless hybrids, the reflected S-parameter of the one port LC termination circuit should be identical to the S21 performance of the whole RTPS. So the design of the phase shifter should be initially focused on the LC termination circuit. There are a lot of possible solutions to make the combination of Ls and C_0 resonate at the desired frequency.

We will call the reflected signal from the termination circuit $S11_T$. Theoretically, the differential phase shift of $S11_T$($\Delta\Phi$) is not only the function of capacitance tuneability($\Delta C/C_0$), but also the function of the capacitance at zero bias field(C_0) and frequency(f). On the other hand, if conductor loss could be neglected, then the return loss(RL) will be determined by the Q of the capacitor (Q_d), its capacitance and the frequency(f). So, the FOM of the termination circuit could be written as:

$$FOM(f,C_0,Q_d,\frac{\Delta C}{C_0})=\frac{\Delta\Phi(f,C_0,\frac{\Delta C}{C_0})}{RL_{V=0}(f,C_0,Q_d)} \qquad (1)$$

Normally, a small value of C_0 (<1pF) is desired for RTPS design because it will lead to large phase shift. But it will also produce a higher return loss which means the FOM value will not change significantly near the resonant frequency of the LC termination circuit.

However, in the actual circuit, additional insertion loss could be found produced by radiation, conductor losses in the termination circuit and reflection loss due to impedance mismatching at the input and output ports. So the FOM of the $S11_T$ signal could be written as:

$$FOM(f, C_0, Q_d, \frac{\Delta C}{C_0}) = \frac{\Delta\Phi(f, C_0, \frac{\Delta C}{C_0})}{RL_{V=0}(f, C_0, Q_d) + extra\_loss} \quad (2)$$

From (2), it is clear that a smaller C_0 will help the termination circuit achieve better FOM performance when there are extra losses. Taking the loss performance of the hybrid circuit into consideration, the influence of C_0 on the RTPS's FOM value will be more significant.

On the other hand, it is well known that smaller C_0 will lead to narrower frequency bandwidth in the reflective phase shifter design. Hence, too small a C_0 is not practically useful because there is always a certain specification on the bandwidth performance. The capacitance of thin BSTO tunable capacitors can be in the range from 0.1pF to 5pF by using different physical structures in their design. The case of thick film BSTO capacitors will be discussed below.

III. FABRICATION AND MEASUREMENT

At the current stage of our research, it is still difficult to control the BSTO material to offer exactly the desired dielectric constant, tunability and tanδ. The best possible reason is due to the variation of the density of the BSTO paste for screen printing, and tolerance of the thickness of printed BSTO patches. In addition, the tolerance on the screen-printing of silver layer will also introduce un-reliability of the capacitor parameters. The tolerance of screen-printing technology is basically limited by the size of mesh hole on the screen. Taking this into consideration, the fabricated capacitor structure will not be identical to the designed one. This will make the design of the device extremely hard with the technology at its current stage of development.

The optimization of BSTO capacitor structure itself is another important issue. Two types of physical design including coplanar through gap structure and vertical gap structure have been examined. Initial result of our capacitor work had been reported in reference[9]. The capacitance of the fabricated BSTO capacitors is ranged from 1pF to 8pF with tuneability from 30% to 55% with a biasing voltage of 100V. The RTPS presented in this paper is roughly designed to work around 2.4GHz. The desired C_0 is 2pF with a tuneability of 50%, Ls is then determined to be about 6mm long.

A photograph of the printed RTPS is presented in figure 2. The BSTO layer is printed in the shape of a long bar with a thickness of 25μm(+/- 5μm). The BSTO material is located in the gap between transmission line Lt and Ls, it helps to form the tuneable capacitor. Silver paste with thickness of 8μm (+/- 2μm) is used to form the main transmission line. The left end of the termination circuit is cut into the desired length then it is edge-grounded via a piece of silver conducting film to the metal package.

The microwave measurement of the termination circuit are made on HP8722ES Network analyzer with the packaged devices mounted in an Anritsu Model 8680V test fixture. DC biasing voltage up to 100V is applied via a DC bias tee with its two electrodes connected to the centre conductor and the ground of the microwave co-axial cable separately.

The microwave measurement result is presented in figure 3. With DC biasing voltage of 100V, the circuit shows a maximum phase shift of 49^o and insertion loss about –2.4dB at 2.5GHz. So the FOM value is about 20^o/dB.

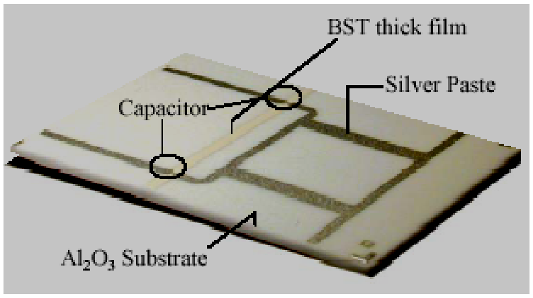

Figure 2. Optical photograph of the sintered RTPS (not edge grounded).

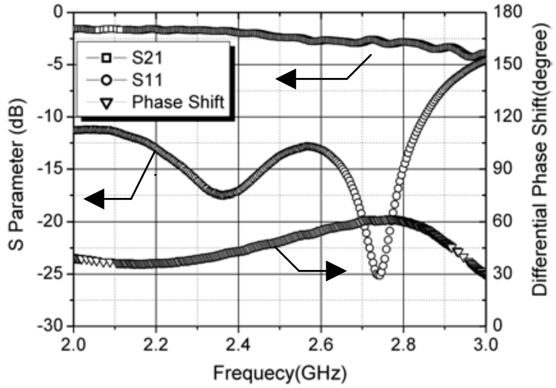

Figure 3. Microwave measurement result of the RTPS.

The FOM of the whole RTPS is about two times lower than the FOM of the termination circuit which has been reported as 54^o/dB [9]. This means that the coupler is introducing about –1dB loss into the RTPS. The explanation of the high insertion loss in the coupler is twofold: the conductor loss and the reflection at the port. Part of the high loss of the device happens in the conducting film used for the edge grounding in the termination circuit. This will cause extra loss because the current density will be high on the grounding conducting film.

IV. CONCLUSION

A ferroelectric thick film reflection type phase shifter working at 2.4GHz is designed and fabricated. With DC biasing voltage of 100V, the phase shifter offers 48^o phase shift with 100V DC biasing voltage and –2.3dB insertion loss. The possible reason for the high insertion loss is discussed and it is clear that better performance could be achieved by further improvement on the circuit design and packaging. As a demonstration, the result is promising and it shows that it is worth carrying out more detailed exploration on this cost effective phase shifter technology.

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