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Thick Film Ferroelectric Phase Shifters using Screen Printing Technology

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***Abstract* — We report the latest development in the ferroelectric thick film technology for microwave applications. Thick film screen-printing technology has become increasingly popular due to its low production cost. Here, we report three types of phase shifter, i.e. Coplanar strip transmission line (cps-tl) phase shifter, transmission line with periodically loaded ferroelectric capacitor phase shifter and reflective resonant phase shifter. All the phase shifters are screen-printed using barium strontium titanate (BST) thick film on alumina substrates. The design and experimental results of these phase shifters are presented.**

I. Introduction

Wireless data communications are growing very rapidly at present due the technological bloom in the 90s. To achieve high efficient data transfer, broadband systems are essential. However, broadband systems cannot easily be achieved at the lower end of the microwave frequency spectrum due to limited availability. This has sparked a huge interest in using the millimetre-wave region [1]. Phased array antennas at millimetre wave frequency are increasing in popularity in communication systems (i.e. point-to-point and point-to-multi-point communication systems). This is due to the efficient usage of bandwidth over the licensed frequency spectrum, as compared to fixed lobe antenna systems. In a phased array antenna, the most important part of the system is the phase shifter. The phase shifters are used to steer the beam in phased array system. A large number of phase shifters are deployed in such a phased array antenna, i.e. one phase shifter per element of the array antenna. Low cost technology for mass production of phase shifters is very important.

Screen-printed thick film ferroelectric phase shifters have high potential in phased array systems because of their low production cost. A large area of BST thick film can be made using screen-printing technology with very inexpensive processing costs. A fully integrated tuneable system will be possible in the very near future.

II. Screen Printing of BST Films

Barium Strontium Titanate (BST) powders with composition of 0.4 $Ba_{0.55}Sr_{0.45}TiO_3$ / 0.6 MgO were used. The BST thick films were fabricated on 99.6% alumina substrates using a conventional screen-printing method. The ink was prepared by combining BST powder together with a commercial vehicle using a three-roll mill at a solids loading of 40 vol.%. The BST films were sintered at temperatures of 1300°C for 2h at a ramp of 5°C/min. Top electrode patterns for phase shifters were also screen printed using silver pastes and fired at 850°C for 20 min.

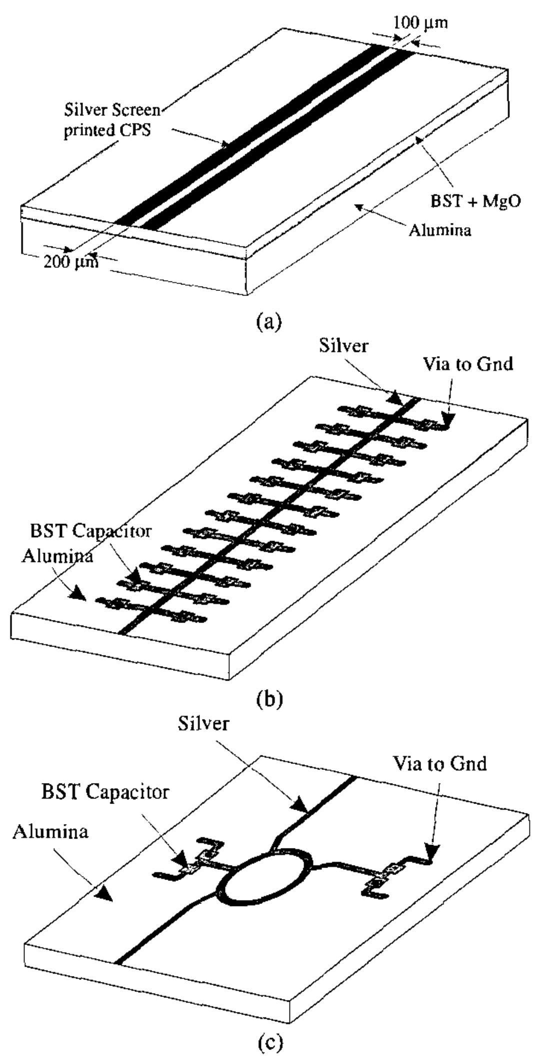


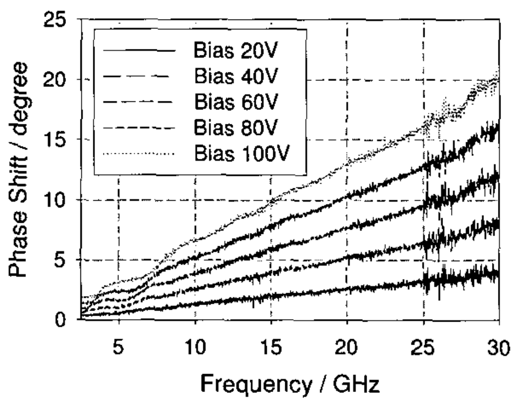
Fig. 1. (a) Transmission line phase shifter, (b) transmission line with periodically loaded capacitor phase shifter and (c) reflective type phase shifter, layouts.

III. Design and Results

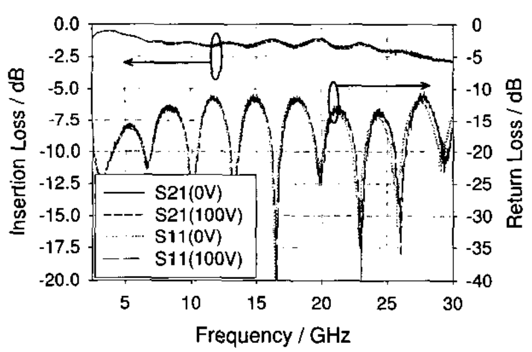
Three phase shifters are investigated and designed in this work. There are the coplanar strip transmission line (CPS-TL) phase shifter, transmission line (TL) with loaded ferroelectric capacitor phase shifter and reflective resonant phase shifter, all the phase shifters are shown in Figure 1.

A. Coplanar Strip Transmission Line Phase shifter

The CPS-TL phase shifter, which consists of two parallel strips with a width of 200μm wide and a gap of 100μm, is a broadband phase shifter. The CPS-TL phase shifter is screen-printed on the surface of the thick ferroelectric film as shown in Figure 1. No ground plane is required in this design.



(a)



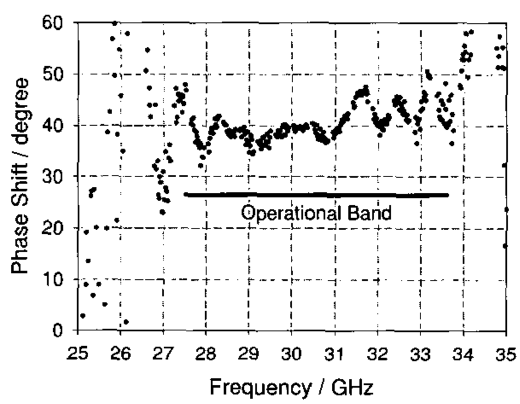
(b)

Fig. 2. (a) Phase shift with different bias voltage (or different applied electric field) and (b) the measured Insertion loss and return loss of the CPS-TL phase shifter.

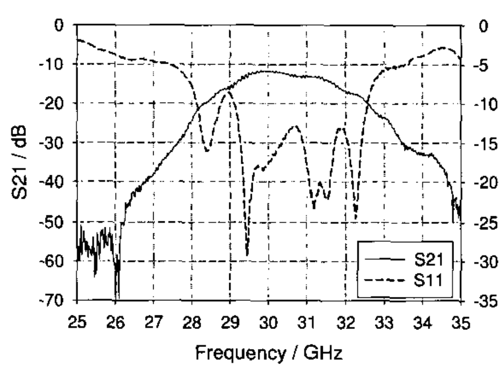
Figure 2 shows the measured phase shift, insertion loss and return loss of the phase shifter at different biasing voltage (or applied electric field). The return loss shows a reasonable good matching has been achieved over the whole 30 GHz band. The measured insertion loss at 30 GHz is approximately 2.6dB. This gives a figure of merit of approximately 8°/dB. At a higher applied electric field, i.e. 10kV/mm, a figure of merit of 80°/dB can be expected. The figure of merit of this phase shifter is more than twice compared to [2] and three time compared to [3] at the same applied field.

B. Transmission Line Phase Shifter with Periodically Loaded Ferroelectric Capacitors

The transmission line (TL) phase shifters with periodically loaded capacitors are well known structure for phase shifters in both ferroelectric and MEMS technologies. As the name suggests, this phase shifter consists of many capacitors connected to the main TL. As the capacitance of the capacitors changes, it changes the loading of the TL. As a result, phase shift can be observed. In the literature, this type of phase shifters is normally operated below Bragg frequency. Therefore, it is limited to low frequency operation. However, we discover that this phase shifter can also be operated above the Bragg frequency if the loaded capacitors are spaced approximately quarter wavelength apart. At approximately twice the Bragg frequency, there is a passband in this structure. Phase shift can also be observed in this passband when the capacitances of the loaded capacitors are changed. The device is shown in Figure 1(b), it is microstrip in form with vias shorting each capacitor to the ground plane.



(a)



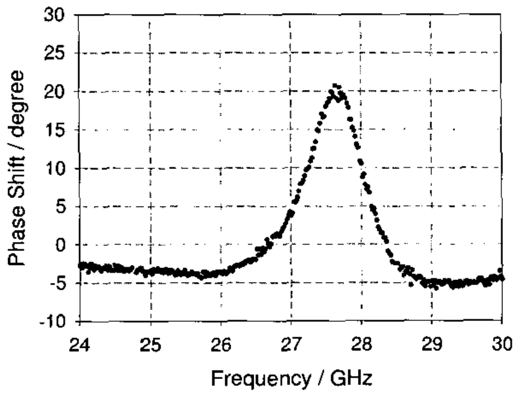
(b)

Fig. 3. (a) Phase shift at 1 kV/mm and (b) the measured insertion loss and return loss of the transmission line phase shifter with periodically loaded BST capacitors.[4]

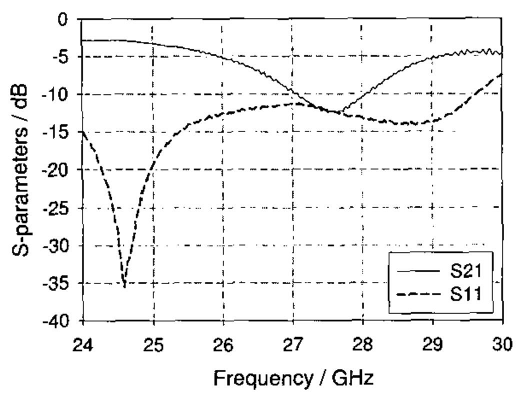
Figure 3 shows the measured phase shift, insertion loss and return loss of the TL phase shifter with periodically loaded BST capacitors. This phase shifter can operate over a 20% bandwidth. The phase shift curve shows a reasonably flat phase shift over this operational bandwidth. This characteristic is more desirable than the TL phase shifter, which increases linearly with frequency.

C. Reflective Type Phase Shifter

The reflective type phase shifter consists of a microstrip hybrid-coupler with two load resonant circuits. The load circuit is fabricated using screen-printed BST capacitors. This is a narrow band phase shifter, which is very popular at low frequency, i.e. below 10 GHz. At high frequency, 27.5 GHz is demonstrated here, matching the hybrid-coupler operation frequency with the load circuit frequency has proved to be difficult due to the small dimension of the overall circuit. To the best of our knowledge, this is the first time a reflective type phase shifter has been achieved at such a high frequency and furthermore this has been achieved using screen-printing technology. Our initial investigation shows some promising results as given in Figure 4.



(a)



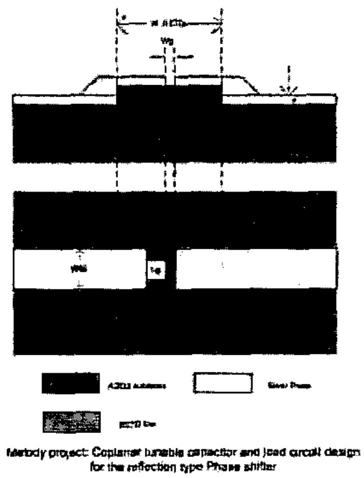
(b)

Fig. 4. (a) Phase shift at 1kV/mm and (b) the measured insertion loss and return loss of the reflective type phase shifter.

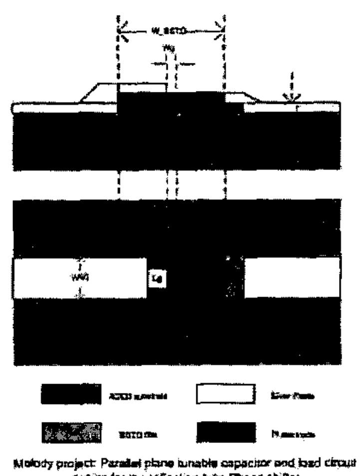
A maximum phase shift of 20° is achieved with a biasing electric field of 1 kV/mm. The loss performance of the circuit is not good at present. We believe this is attributed to the poor screen-printing of the small area, which is used for the fabricating of BST capacitors. To further improve this phase shifter, we have investigated the correlation between capacitor structures with the printing process. A summary of this study is given in the next section.

IV Optimizing Tunable Circuits

We have preformed a study on the capacitor structure to optimise the screen print process. Two types of capacitor structures were used in this study. There namely the coplanar capacitor and the vertical capacitor structures, which are shown in Figure 5(a) and (b), respectively.



(a)



(b)

Fig. 5 (a) Coplanar capacitor structure and (b) Vertical capacitor structure

To further improve the thick film BST phase shifters, we have broken down the phase shifters into small tunable circuits to optimize the printing technique for the phase shifter structures. The small tunable circuits can be seen as the load circuits of the phase shifters, which are also the most crucial components in the phase shifter structures. This study was preformed at 2 GHz range.

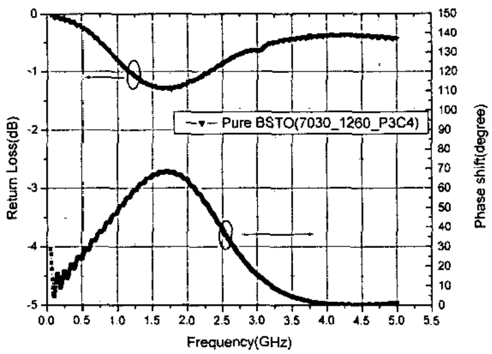


Fig. 6 Measured performance of the vertical capacitor structure load circuit.

From our studies, we discovered that the vertical structure capacitor is better. A figure of merit of approximately 54 degree/dB has been achieved using the vertical capacitor structure. However, this figure of merit is only for the load circuit. The coupler is excluded in this measurement and the performance of the load circuit is the measure of the reflection loss divided by the reflection phase shift as shown in Figure 6.

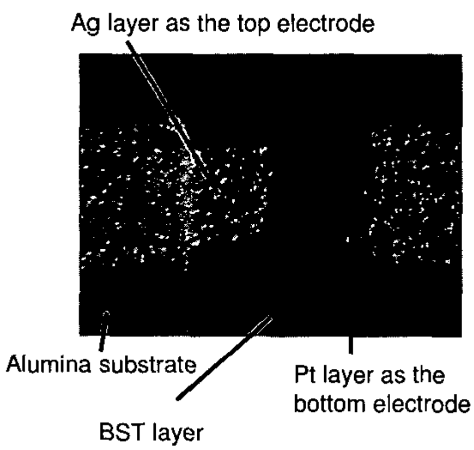


Fig. 7 Optical microscopy photograph of the screen printed vertical capacitor structure

Figure 7 shows the optical microscopy photo of the screen-printed vertical capacitor structure. Due the low sintering temperature of silver, platinum layer is used for bottom electrode, i.e. underneath the BST layer. The platinum layer is co-fired with the BST layer while the silver layer is fired after the platinum and the BST layers. A good printed circuit has been realized with minimum gap and line width of 100μm.

IV. CONCLUSION

We have demonstrated three different types of phase shifter achieved using screen-printing technology at high frequency. Both the conductors and the thick film BST are screen-printed whereas in [3], the conductors are realized using thin film technology, which effectively are more expensive to manufacture. We have shown promising future for the screen-printing technology. Some studies on the optimization of the screen-printed capacitor structures were also presented.

Every effort has been put to further improving the printing processes to further improve the microwave properties of these devices. At present, the screen-printing technique used is not fully optimized for printing small areas and more studies are under way. Once this is achieved, a much improve circuit performance can be expected.

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