Distributed Transmission Line Phase Shifter with Loaded BST Capacitors using Thick Film Technology

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Abstract

A thick-film phase shifter fabricated from screen-printed ferroelectric capacitors and metallization is described. At 30 GHz a phase shift of 4°/dB at 1kV mm^{-1} was achieved. The phase shift less dependent on frequency than conventional transmission-line phase designs

1. Introduction

Phase shifters are important components in communication systems, especially in phased array radar systems and steerable antenna systems for beam forming networks. Hundreds of phase shifters are usually deployed in a phased array radar system. Therefore, it is important that phase shifters are produced at a very low cost.

Here, we present a cost effective technology for fabricating tuneable components, such as phase shifters. This technology employs screen-printing techniques to achieve the ferroelectric layers, which are used for tuning the device, and also the metallization used for the electrodes.

Barium Strontium Titanate (BST) is well known in thin film technology for its high permittivity, which can be in the range of a few thousands, and its high tuneability. It is used widely in designing tuneable microwave components [1-3]. For thick film technology, it receives less attention. The permittivity of the thick film is crucial as the thickness of the tuneable layer increases, because it forms part of the substrate. Very high permittivity substrate will shrink the circuit down considerably and, therefore, it is difficult to design and screen-print any useful circuits. Here, we employ BST composition of 55% Barium and 45% Strontium together with Magnesium Oxide (MgO) as a dopant to reduce the permittivity of this ferroelectric material and also maintain a relatively good tuneability.

For the phase shifter, we have chosen a well known structure, which is a distributed transmission line with loaded tuneable capacitors or varactors [4-5]. The tuneable capacitors are achieved using BST material where the capacitance can be altered with a DC bias voltage.

The periodically loaded transmission line with tuneable capacitors is normally operated below the Bragg frequency [4-5]. This limits the operation frequency of this structure. Here, we propose to operate this phase shifter above the Bragg frequency. We have shown that operating at its harmonic not only raises the operating frequency but also provides some additional advantages. A detailed discussion with some experimental results will be presented.

2. Phase Shifter Model/Design

The distributed transmission line phase shifter with loaded BST capacitors can be modelled using a transmission line model. Figure 1 shows the transmission model used for circuit simulation, which was performed using AWR Microwave Office. Conventionally, the loaded capacitors are distributed very much shorter than a wavelength.

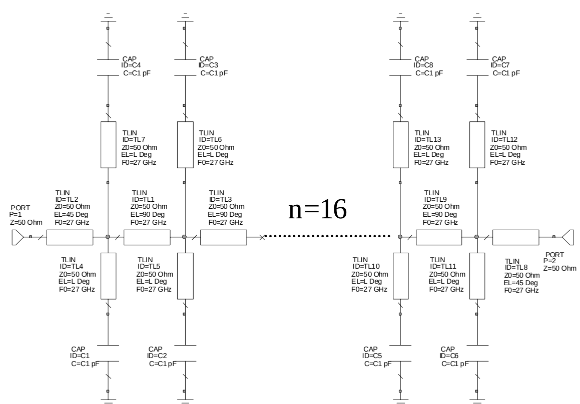

Figure 1. Circuit model of the phase shifter

In this design, the loaded capacitors are distributed a quarter wavelength apart at the operating frequency. The load circuit consists of a transmission line and a capacitor shorted to ground. The length of the transmission line, L, in the load circuit is designed to be approximately 100° in electrical length at the operating frequency and the initial capacitance of the capacitor is approximately 0.4pf.

Figure 2 shows the wide band response obtained from the circuit simulation (S11 and S21). The Bragg frequency of the phase shifter is approximated 8 GHz. At approximately twice the Bragg frequency, a second passband is obtained. At the centre frequency of the second passband, i.e. the operating frequency of the phase shifter (27GHz), a very good matching is obtained.

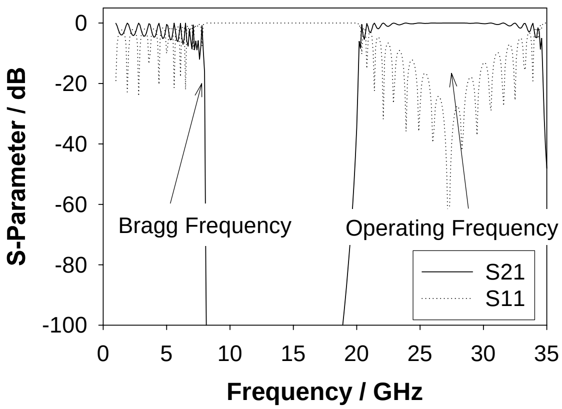

Figure 2. Wide band response of the circuit model

A phase shift can be obtained by tuning the capacitors in the load circuit. Figure 3 shows the simulated phase shift of the phase shifter with up to 20% tuning in the capacitance value. Higher phase shift can be obtained by using more load circuits.

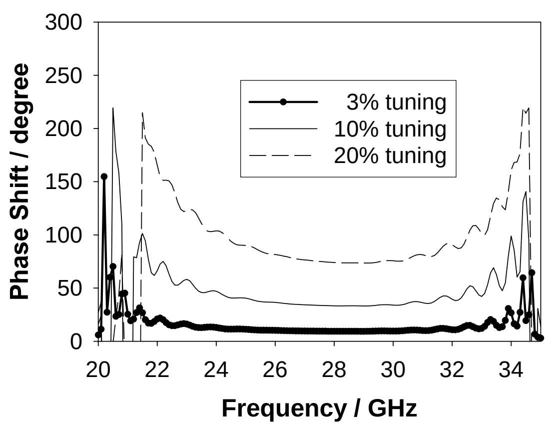

Figure 3. Phase Shift due to changes in capacitance

A full wave electromagnetic simulation on the phase shifter was also performed to ensure the validity of the phase shifter operation. Figure 4 shows the comparison between the EM simulated response (using EM Sonnet) and circuit model simulated response. The S-parameter responses show a reasonably good agreement between the two. However, there is some slight discrepancy if one makes a closer inspection. This is mainly due to the crude capacitor model used in the circuit simulator, which is frequency independent.

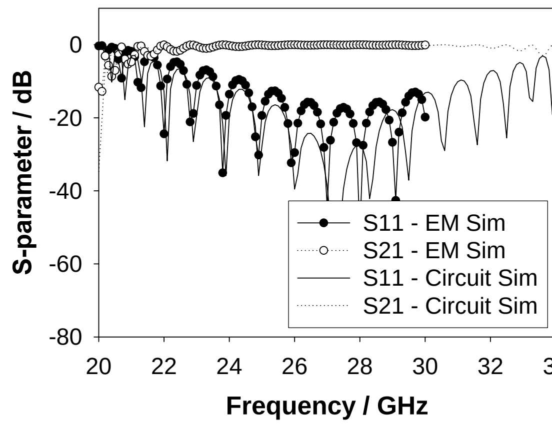

Figure 4. Comparison between circuit simulation and electromagnetic simulation

3. Screen Printing of BST Film

Barium Strontium Titanate (BST) powders with composition of 0.4 $Ba_{0.55}Sr_{0.45}TiO_3$ / 0.6 MgO (Filtronic Comtek, UK) were used. 2 wt.% boron silicate glass powder was added as a sintering aid to reduce the sintering temperature and yet maintaining a high-density film. Patterns of vias of 0.1 mm diameter were first micromachined using laser on 50x50 mm 99.6% alumina substrates with thickness of 0.254 mm. BST thick films were fabricated using a conventional screen-printing method.

The BST powder combined together with a commercial vehicle (Blythe 6321 Medium) using a three-roll mill at a solids loading of 40 vol.% was used to prepare the BST ink for screen-printing. The BST films were sintered at temperatures of 1200°C for 2h at a ramp of 5°C/min. Top electrode patterns for phase shifters and ground electrode were then screen printed using silver pastes and fired at 850°C for 20 min. The dielectric properties at low frequencies have been characterised using an impedance analyser (HP 4901) from 70 to –70°C.

Figure 5 shows the dielectric properties (at 10 kHz) and tuneability (at 0.8 V/μm DC field) of the BST films sintered at 1150, 1200 and 1250°C, respectively. The permittivity increases with sintering temperature due to improved densification of BST films. The tuneability increases most significantly in the ferroelectric region. The dielectric loss is generally <0.005 over the measurement temperature range. Considering the dielectric properties and adhesion between the film and substrate, the sintering temperature for phase shifter was chosen as 1200°C.

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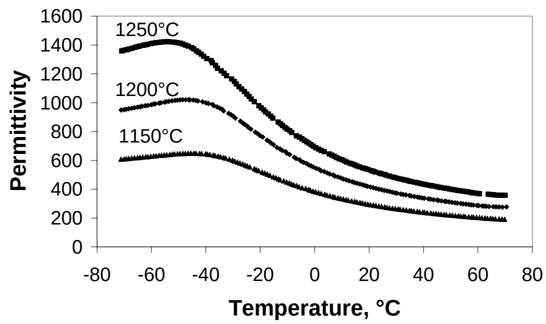
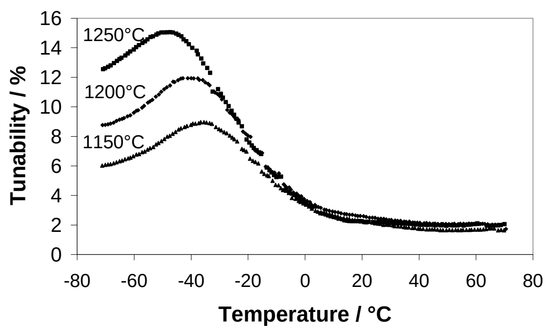


(a)



(b)

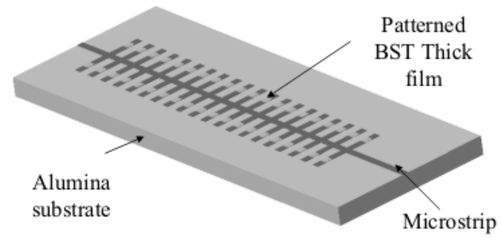
Figure 5. (a) Dielectric properties (at 10 kHz) (b) tuneability (at 0.8 kV/mm DC field) of BST films sintered at different temperatures

4. Measurement and Results

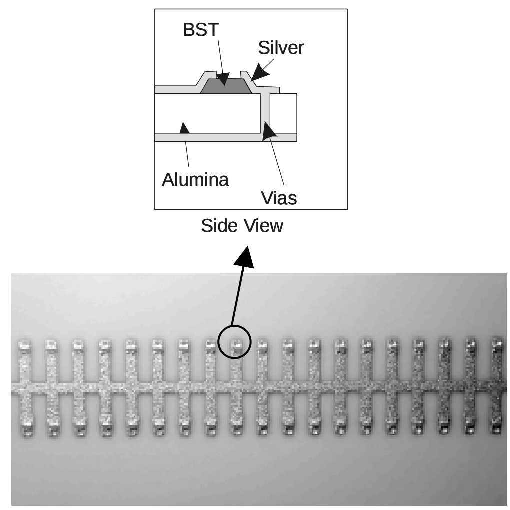
Figure 6(a) shows a 3 dimensional model of the distributed transmission line phase shifter with periodically loaded BST capacitors and Figure 6(b) shows the actual screen-printed phase shifter. The fabricated phase shifter consists of 40 parallel stubs/load circuits, which is two times longer than the simulated structure.

The BST capacitor in the load circuit is designed using a coplanar structure with one end shorted to ground as shown in the inset of Figure 6(b). The gap between the transmission line and the grounded end is approximately 100µm. These electrodes are sitting one top of a BST layer, which has a thickness of approximately 10µm. The width of the microstrip used is 300µm, which gives an impedance of approximately 50Ω on the alumina substrate.

The phase shifter was measured using an HP8510 network analyser with external bias tees. The phase shifter was measured with a biasing voltage of 100V, which correspond to electric field strength of approximately 1 kV/mm.



(a)



(b)

Figure 6. (a) 3D view of the phase shifter (b) Optical microscope picture of the screen-printed phase shifter

Figure 7 shows the difference in phase shift between zero bias and a field of 1 kV/mm. One of the advantages shown on the graph is the relatively flat phase shift over wide frequency range as compared to a pure transmission line phase shifter where the phase shift varies linearly with frequency [6].

The measured operating frequency is around 30GHz, which is slightly higher than designed. This slight shift in frequency can be attributed to a few factors. The exact dielectric constant of the BST at 27GHz is unknown because the BST film has only been characterised at low frequency, i.e. 10kHz. The thickness of screen-printed BST is difficult to control. A different BST thickness will give rise to a different capacitance. These are the main two factors that we believe to cause the frequency shift in the design.

The measured phase shift is higher than the modelled because the fabricated phase shifter has twice as many load circuits. The estimated tuneability of the material is approximately 3% at 1kV/mm. From the model, we expect about 20° phase shift (two time of the value in Figure 3) but we achieved twice this value.

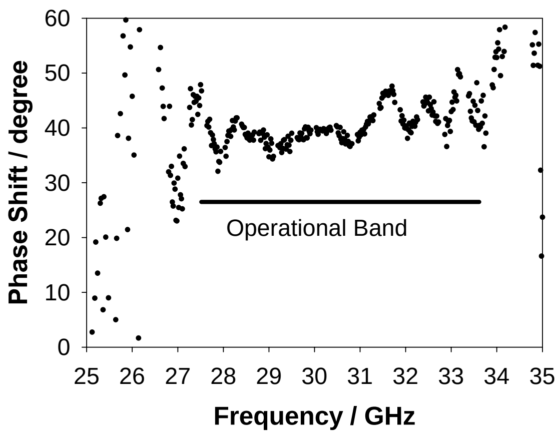


Figure 7. Experimental result of phase shift at low field

Figure 8 shows the insertion loss and the return loss of the phase shifter. The measured insertion loss is approximately 10dB at the 30GHz and the return loss is better than 10dB, which shows a reasonably good matching. This gives a figure of merit of about 4 °/dB at applied electric field strength of 1kV/mm.

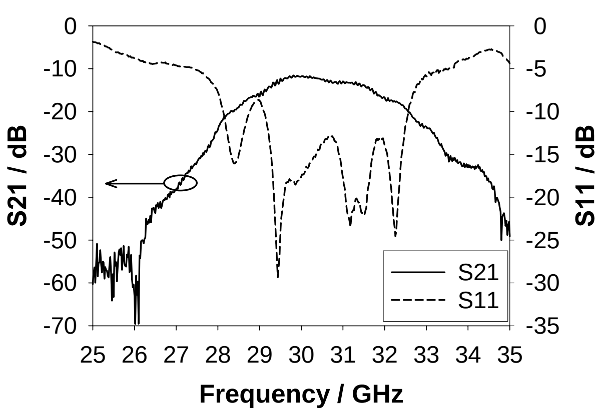


Figure 8. Experimental result of the S-parameter responses

The figure of merit can be further improved by applying higher electric field. We have shown that with 0.8 kV/mm of electric field strength (from the low frequency characterisation), we are only exploiting approximately 2-3% tuneability of the BST material. We believe this tuneability can be improved with increases field strength.

5. Conclusions and Future Work

We have shown a phase shifter working above Bragg frequency using screen-printing technology. The concept of this phase shifter has been proven using circuit simulation, EM simulation and experimental. Promising results have been achieved in the fabricated phase shifter. However, in term of the phase shifter performance, much improvement is needed. The achieved 4 °/dB is not yet useful for device application.

To further improve the performance of the phase shifter, some improvement in the printing technique is required. The line edge of screen-printing will never be as good as photolithography but the cost effectiveness of screen-printing will still make it an very attractive technology. We believe there is still a lot of room for improvement in edge profile of the achieved screen-printed silver. Printing thicker BST layer is also of one the direction we are pursuing to further improves the phase shifter.

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