

Thin-Film Phase Shifters for Low-Cost Phased Arrays

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Abstract:

Drastic cost reduction of phased-arrays will require a shift in design strategy. The emphasis must be on removing expensive active components, not developing more highly integrated components or exotic packaging techniques. The phase shifter circuit—an essential active component—is the primary obstacle in decreasing the cost and number of active components in a phased-array. The problem is multi-faceted: (1) current phase-shifter components are expensive MMICs (~40% of a typical receive-array cost); (2) MMICs require careful packaging, further increasing costs; and (3) current phase shifters have significant RF loss and therefore additional amplification must be provided to compensate for this loss, which in turn may require limiting circuits (in a receive application in situations with strong local interference). If a phase shifter could be designed with little or no loss, it is believed that up to 80% of the active devices in a typical phased-array could be deleted from the design.

Two new technologies—thin-film nonlinear dielectrics and MEMS—have recently emerged and show significant promise for implementation of low-loss and low-cost phase shifters. Both technologies appear capable of ultimately providing <3dB insertion loss for a 360 degree phase shifter at considerably lower cost than existing MMIC designs. This paper will focus mostly on developments in thin-film phase shifter circuits using monolithic Barium Strontium Titanate (BST) varactors on inexpensive substrates. Enhanced MEMS circuits using such thin-film dielectrics will also be discussed and contrasted with the nonlinear dielectric approaches in terms of electrical performance and practical considerations for use in low-cost phased-arrays. The thin-film nonlinear dielectrics have been grown by both MOCVD-grown and RF magnetron-sputtering, and can now be obtained commercially. They are very inexpensive, can be deposited on inexpensive Silicon or ceramic substrates, and are compatible with most standard monolithic processes with considerably looser lithography requirements as compared with MMICs. Current progress in materials and projected performance limits will be discussed.

Thin-Film BST

Barium Strontium Titanate ($\text{Ba}_{1-x}\text{Sr}_x\text{TiO}_3$, or simply BST) thin films have an electric-field-dependent permittivity, making them suitable for several linear and nonlinear circuit applications at microwave frequencies. Until recently, the use of BST in microwave circuits was impractical due to the high microwave losses associated with these materials. However, there have been numerous advances in the deposition technology for BST in thin-film form, mostly for use in small-area storage capacitors in high-density silicon DRAM [1], which have subsequently lowered microwave losses in BST thin films to levels where they are now practical for circuits. In addition to tunable permittivities and low losses, these materials also have high breakdown field strengths leading to high power handling capability.

Most of the research on microwave applications of BST has focused on wave propagation in bulk crystals or thick films [2]. Although bulk (ceramic) BST has been demonstrated with low RF loss tangents, the bulk approach can nevertheless result in high microwave losses as a consequence of the extremely high permittivity of the bulk material (a large substrate dielectric constant indirectly leads to large ohmic losses on transmission lines due to changes in the conductor geometry required to maintain a specified characteristic impedance). Bulk BST has a very strong temperature dependence, exhibiting a well-defined and composition-dependent Curie temperature near room temperature. In contrast, thin-film BST can have remarkably different electrical properties than bulk BST. Figure 1 compares the temperature-dependent zero-bias permittivity of bulk material and MOCVD-grown thin-film BST (on Pt-coated Silicon) of roughly the same composition. The low-field permittivity is dramatically reduced from >4000 at room temperature for bulk material to something in the range of 200-350 for the thin-film material. It is believed that mechanical stress in the film due to growth on thermally mismatched substrates is largely responsible for this behavior.

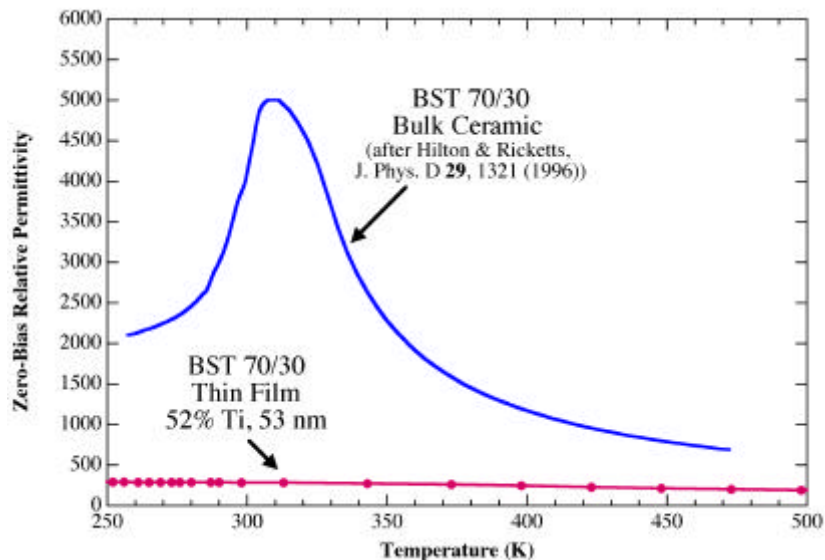


Figure 1— Comparison of zero-bias dielectric constant for bulk BST and thin-film (MOCVD-grown) BST versus temperature.

Attractive features of BST materials and devices are described in figure 2, along with promising circuit applications. Integrated parallel-plate or interdigital BST-based capacitors may be used as replacements for semiconductor varactor diodes in several linear and nonlinear microwave circuit applications. Thin-film varactors offer several advantages over semiconductor varactor diodes: They are easy to fabricate and can be made at lower cost than semiconductor varactor diodes; They have higher breakdown field strengths and thus have higher power handling capability than semiconductor diodes. Like semiconductor diodes, the nonlinear capacitance can also be exploited to make frequency conversion devices (multipliers, mixers, etc.).

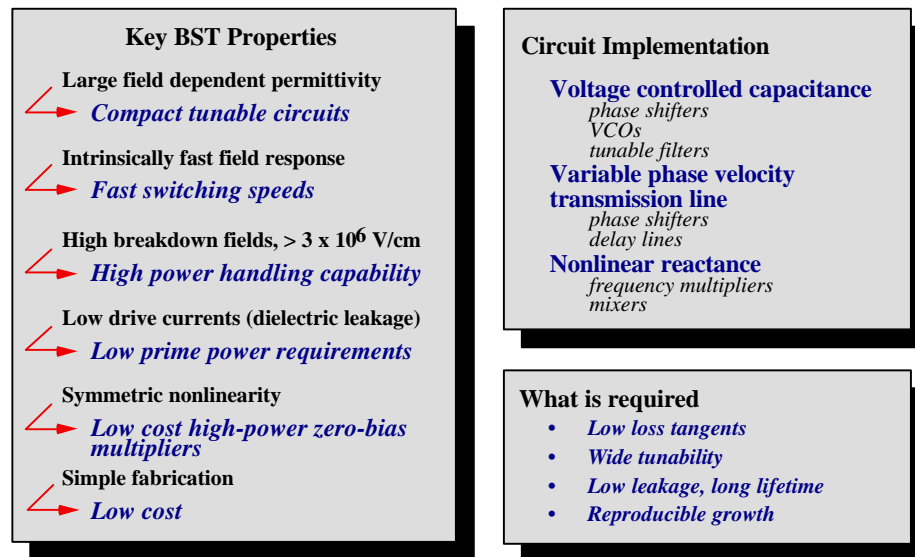


Figure 2 — Summary of BST merits and potential for use in circuits.

Chemical Vapor Deposition (MOCVD) and RF Sputtering are the two most promising methods for deposition of high-quality BST thin-films on commercially viable substrates. At UCSB, RF sputtering is favored since it allows for growth at somewhat lower temperatures than MOCVD and hence affords greater flexibility in terms of substrate and electrode choices. The sputtered BST thin films can be deposited on a number of semiconductor or microwave substrates such as silicon, GaAs, MgO, alumina etc. which have reasonably low permittivity thus helping to reduce overall circuit loss. The ability to deposit sputtered BST thin films on standard microwave/semiconductor substrates also has benefits from a cost and compatibility standpoint since thin film processing techniques are widely used in the semiconductor and microwave industry. Microwave circuits also tend to be physically large, making them cost-prohibitive on precious semiconductors such as GaAs. Sputtered film deposition is also much cheaper than semiconductor epitaxy.

Integrated Monolithic BST Varactors

Currently, BST thin film based varactors have similar loss performance to GaAs Schottky varactor diodes, for a given set of lithographic design rules. But with further improvements in

material quality it is likely that they will have superior loss performance. Recent studies [1] have demonstrated extremely low RF losses up to 20GHz, corresponding to loss tangents of less than 0.003, or device Q-factors of >300 . UCSB has focused on the development and optimization of BST thin-films specifically for microwave integrated circuits, using both MOCVD-grown and RF magnetron-sputtered films. The material optimization efforts have concentrated on achieving high tunability and simultaneous low loss, and also developing suitable electrode systems for circuit fabrication on silicon substrates. Currently we have achieved 4:1 tunability in the dielectric constant with loss tangents of 0.003 (@ 1 MHz) using sputtered material.

The materials have been incorporated as monolithic microwave integrated capacitors in thin-film phase-shifters circuits using Pt-coated silicon substrates, with direct growth of the BST on the Pt. Figure 3 illustrates a simple parallel-plate capacitor structure integrated in shunt along a coplanar transmission-line (CPW). For lowest possible loss, the silicon substrates can be micromachined in the CPW gap region. This also has the advantage of reducing the capacitance per unit length on the unloaded-line, allowing for larger capacitive loading in a circuit. Figure 3 also shows a typical capacitance versus voltage curve for the parallel plate devices fabricated at UCSB, on a 100nm film with a zero-bias dielectric constant of ~ 300 .

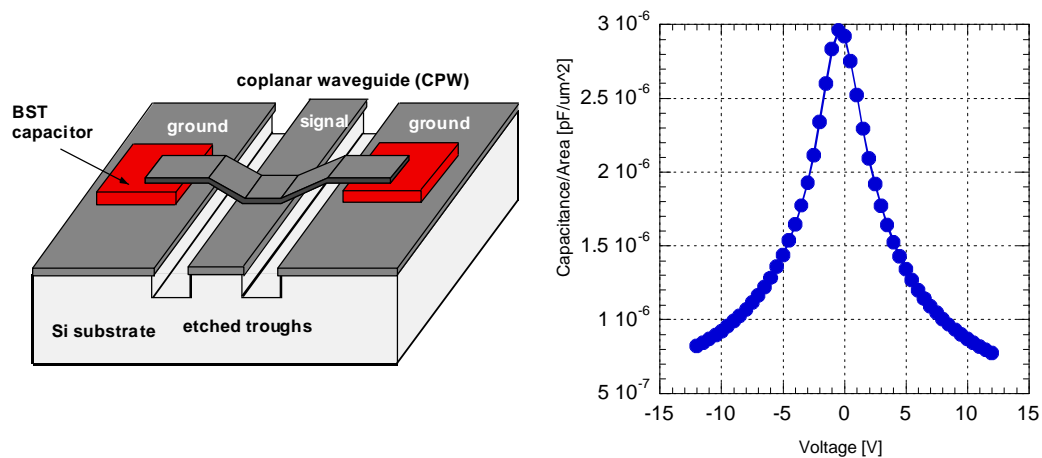


Figure 3: a) Integrated thin-film capacitor structure on a coplanar waveguide. b) Low-frequency (1 MHz) C-V curve of a typical UCSB device showing 4:1 capacitance variation.

Monolithic delay lines are then implemented using this technology. The delay lines are distributed circuits using a coplanar waveguide periodically loaded with thin-film BST varactors, as shown in figure 4. When designed correctly this structure is a synthetic transmission line with a phase velocity that can be controlled by changing the value of the external loading capacitors. The parallel plate capacitor topology utilizes the tunability of the BST film effectively and requires lower control voltages than interdigital designs. Conductor losses are low in this topology since the transmission lines are fabricated on low dielectric constant substrates such as HR-silicon (as opposed to bulk ferroelectric) substrates.

Nonlinear applications of such varactor loaded lines have been previously demonstrated with considerable success [3,4]. The use of this topology for *linear* applications is now gaining

popularity, and UCSB has been a leader in the development of low-loss phase distributed shifters [5-6]. UCSB has recently demonstrated analog phase shifter circuits using monolithic GaAs varactors loading a coplanar waveguide (CPW) transmission line in K-band, resulting in < 4 dB insertion loss at 20 GHz and a continuously programmable delay of 0-360 degrees at this frequency.

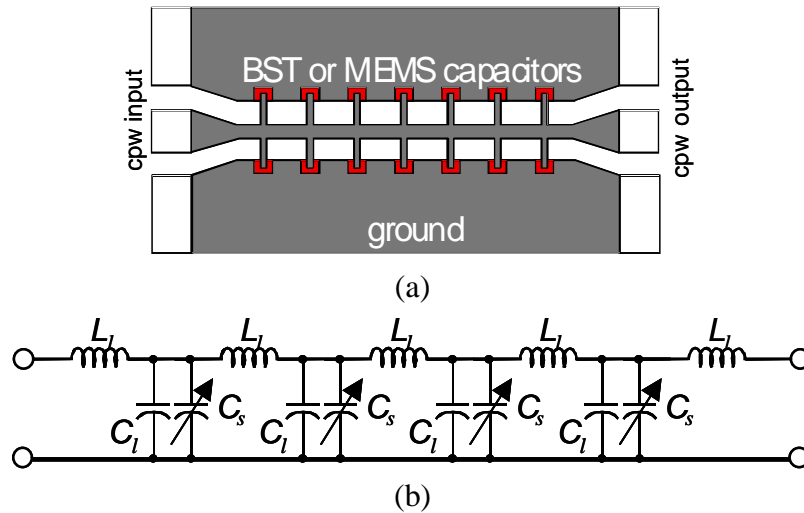


Figure 4: (a) Distributed circuit phase shifter using a periodically-loaded coplanar waveguide. (b) Equivalent circuit of the distributed phase shifter.

The excellent performance of the phase shifters fabricated at UCSB was the result of careful modeling of the circuit, especially with respect to RF losses, which allowed us to optimize the structure for low insertion loss and high performance. An especially important parameter is the loading factor 'x', which is the ratio of the variable capacitor per unit length to the unloaded line capacitance per unit length. For a given variable capacitor technology and substrate dielectric constant there exists an optimum loading factor which results in a circuit with lowest possible insertion loss. This has been experimentally verified by measuring the losses on GaAs varactor loaded transmission lines, and it was found that losses for the optimally loaded transmission line are dominated by the losses in the variable capacitor. Thus, further efforts to reduce the losses of the circuit must concentrate on reducing losses in the variable capacitor, which we seek to do using thin-film BST technology.

To demonstrate the potential of BST thin film capacitors, we have analyzed phase shifter circuits that use BST based variable capacitors as the periodic load elements. The analysis was carried out for different substrate dielectric constants and for different values of loss tangent of the BST film. The results of our analysis are interesting and show that for minimizing the total circuit loss there exists a certain optimum loading factor. As shown in figure 5a the optimum loading value is different for substrates with different dielectric constants. More importantly, the total circuit loss decreases with a decrease in the substrate dielectric constant. This suggests that part of the reason why diode-based nonlinear transmission line circuits are so lossy (in addition to high diode losses) is that they are fabricated on GaAs substrate which has a relatively high dielectric constant (~ 13) leading to

high conductor losses. However since the proposed technology allows a range of substrates to choose from it is not subject to the same limitations. Another set of calculations we performed was to investigate the effect of the BST thin film loss tangents on the total phase shifter losses and the results are shown in figure 5b. At loss tangents of 10^{-3} or lower (specified at 10 GHz) the performance is limited by conductor loss only, indicating that significant improvements over diode-based circuits can be obtained with material improvements.

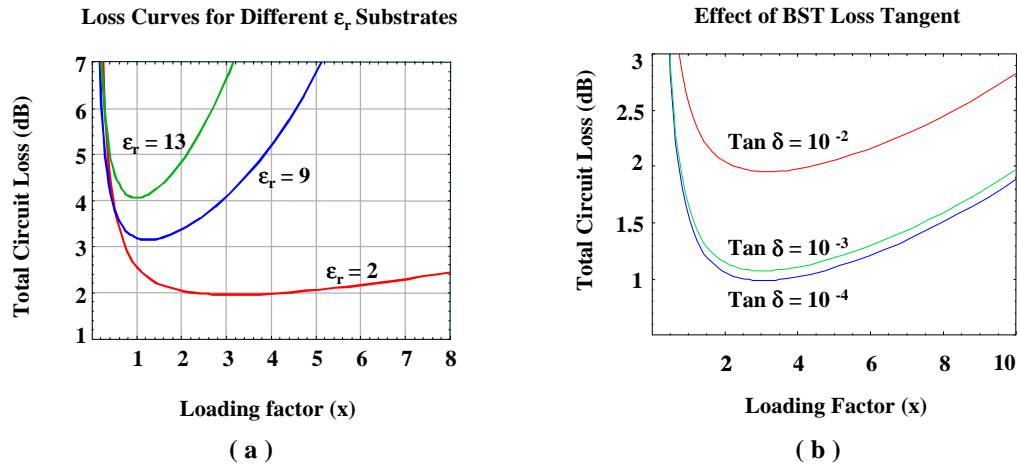


Figure 5 – Predicted losses for BST-based circuits like that of fig.3. (a) Influence of substrate dielectric constant ($\text{tan}\delta=0.02$, or $Q=50$); (b) Influence of loss tangent ($\epsilon_r=2$).

UCSB has recently demonstrated a BST-based periodically loaded line phase shifter as shown in figure 6. The phase shifter was capable of producing up to 160° of phase shift at 30 GHz. The phase shift increases linearly with frequency as expected for a variable time delay element. The preliminary results of this phase shifter are shown in figure 7. Note that this phase shifter has not yet been fully optimized, however the result seems to confirm the potential of thin film BST technology. Advances in the materials are required to further improve on this result.

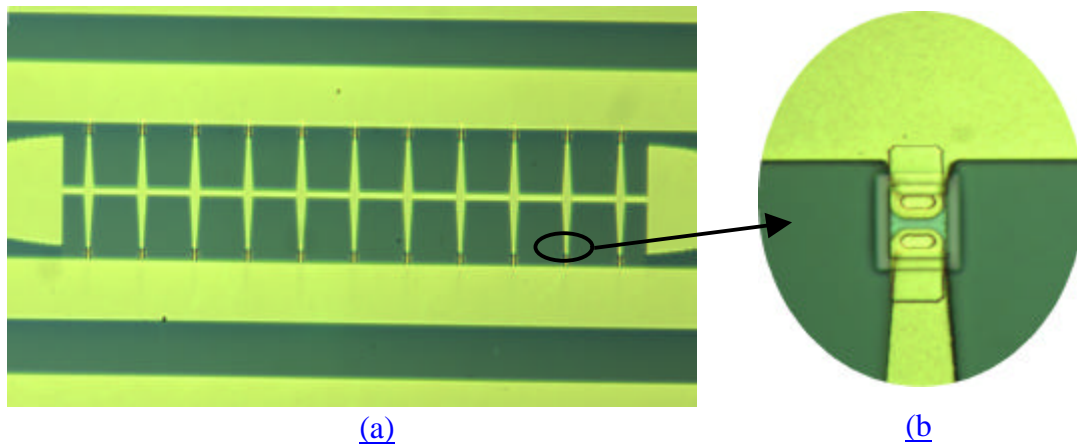


Figure 6: a) Photograph showing a periodically loaded line phase shifter fabricated at UCSB. b) Details of parallel plate BST capacitor used in the circuit.

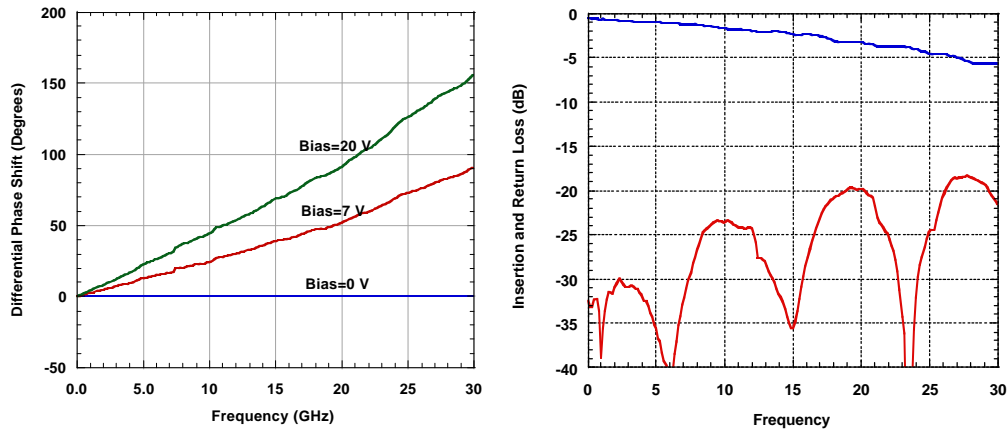


Figure 7: Measured performance of a periodically loaded line phase shifter fabricated at UCSB.

Enhanced MEMS Switches

Micro-Electro-Mechanical Systems (MEMS) concepts have been successfully applied in the past few years to the development of low-loss RF switching devices and variable capacitors [10-12]. The capacitive switch in figure 8 is a widely used approach, exploiting an electrostatic attraction between a flexible metal membrane suspended over a lower conductor. Such devices have been used to realize switched-line phase shifter circuits with significantly lower loss than can be realized using conventional semiconductor switch technology [10].

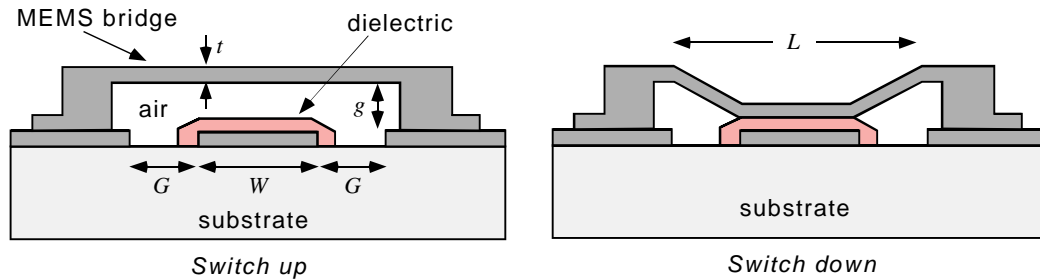


Figure 8: Cross-section of a MEMS capacitive switch in a CPW configuration.

In the capacitive switch of figure 8, low insertion loss (in the off/up state) and high isolation (in the on/down state) are obtained by maximizing the capacitance ratio between the on and off states. If the dielectric coating on the bottom conductor is very thin, this capacitance ratio can be expressed as

$$\frac{C_{on}}{C_{off}} \approx 1 + \epsilon_r \frac{g}{h}$$

where g is the air-gap, h is the dielectric thickness, and ϵ_r is the dielectric constant of the insulator coating the lower conductor. Clearly we wish to maximize the g/h ratio, however there are limits on this ratio imposed by pull-down voltage requirements, dielectric breakdown, and processing considerations. However, we can see from this expression that

the use of a high dielectric constant film such as BST can dramatically increase the capacitance ratio. Many current switch technologies utilize SiN or SiO₂ films with dielectric constants on the order of 4. Using BST with $\epsilon_r \approx 300$ allows us to improve the capacitance ratio by a factor of 75!

Switched-Capacitor Phase Shifters

Membranes like that of figure 8 have recently been used to implement a varactor-like delay phase shifter similar to that of figure 4 [13]. In this case an analog control voltage was used to vary the height of the MEMS bridge *without inducing the snap down*, resulting in a limited capacitive ratio C_{max}/C_{min} (<1.5). An alternative approach using MEMS switches is shown in figure 9. In this case, a binary-state capacitance is used to switch the circuit between two delay states. A sequence of such circuits can then be cascaded to provide the desired incremental delay states, similar to a conventional switched-line phase shifter.

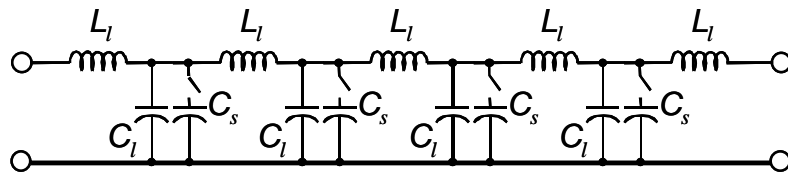


Figure 9: Switched-capacitor delay line.

The design considerations for the circuit of figure 9 are somewhat different than for a low-loss MEMS switch, since the circuit requires a relatively small value of loading capacitance per unit length. The fabrication of physically small MEMS switches can be a challenge, resulting often in a drawback of very high actuation voltages. We have proposed an alternative design using a series capacitor, fabricated as part of the MEMS switch as shown in figure 10 [14]. The series capacitor effectively reduces the overall capacitance of the switch, allowing for larger contact area and resulting in a better reliability of the fabrication, reduced pull-down voltage, and a high capacitive ratio (>10).

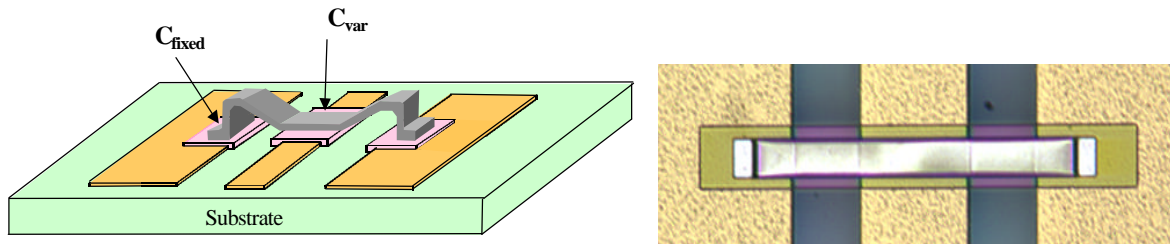


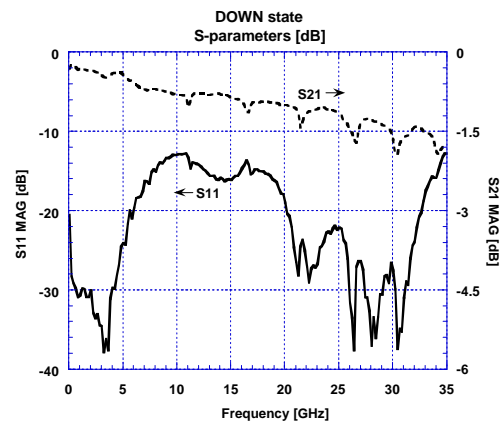
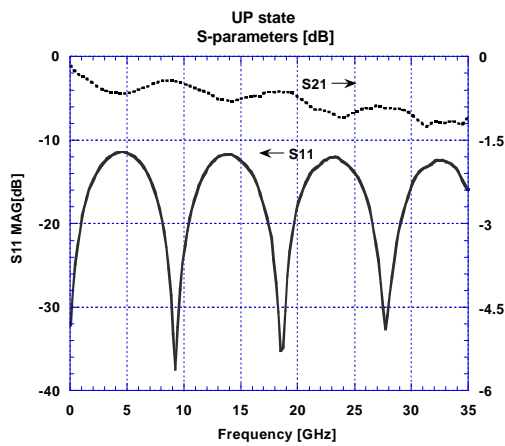
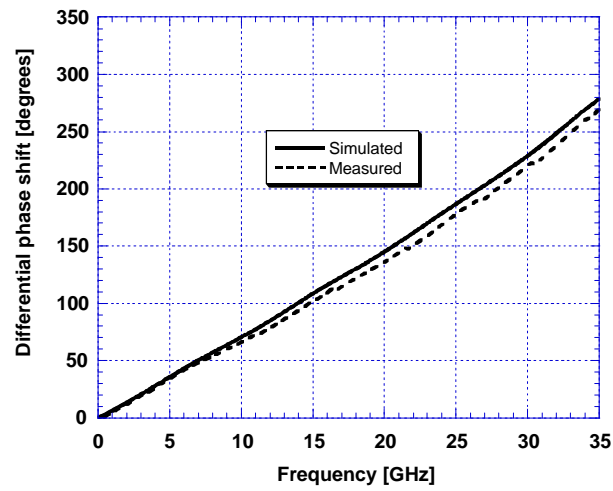
Figure 10: MEMS capacitive switch using a series capacitor. (Left) plan view, (right) photo of UCSB switch [14].

Using this switched-capacitor concept, we have implemented a 1-bit (180 degree) phase delay network [14]. A photo of the completed circuit is shown in figure 11, and the measured performance is given in figure 12. Although the results presented are for 1-bit phase shifter, it is simple to extend the fabrication and design technique to a multi-bit digital distributed MEMS phase shifter, by means of a simple length scaling of the circuit design.

The current design is capable of producing 360° phase shift with 2.34 dB loss at 25GHz and with 2.25 dB loss at 35 GHz, which is state of the art performance for K/Ka band phase shifters.



Figure0: Switched-capacitor delay line.



Conclusions

Exciting progress has been made in the development of low-cost RF phase shifters. However, there is significant room for improvement in both material and circuit performance, and we will highlight particular areas for further research in this presentation. Ultimately this technology is expected to yield commercially viable phase shifters with <3dB insertion loss at frequencies up to 40GHz and beyond, making this an extremely attractive technology for low-cost mm-wave phased arrays.

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