# Affordable Phase Shifters

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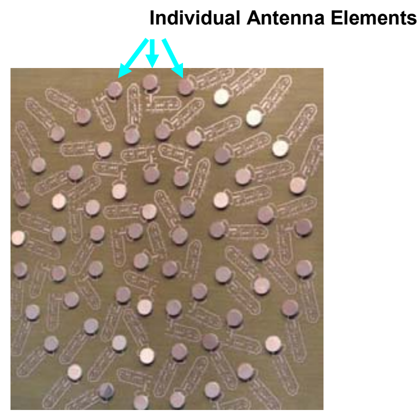
## INTRODUCTION

Phase shifters are critical elements for electronically scanned phased array antennas and typically represent a significant amount of the cost of producing an antenna array. Phase shifters are the devices in an electronically scanned array that allow the antenna beam to be steered in the desired direction without physically re-positioning the antenna. It is not uncommon for the cost of the phase shifters to represent nearly half of the cost of the entire electronically scanned array. This excessive cost has limited the deployment of electronically scanned antennas and made their use restricted to expensive and specialized systems such as fighter aircraft radar and certain commercial systems such as cellular telephone base stations. There is significant demand in the wireless and microwave industries for affordable phase shifters that can reduce the cost of an electronically scanned antenna system and allow them to be deployed more widely. Additionally, phase shifters provide an elegant way of linearizing amplifiers for such applications as cellular base stations. This paper will provide further detail on why this is so and explore avenues for lowering the cost of phase shifters.

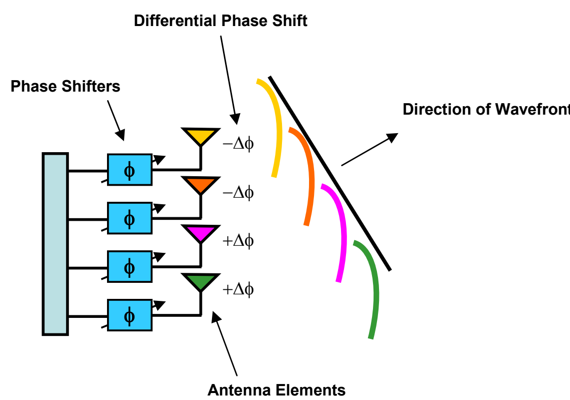
## ELECTRONICALLY SCANNED ANTENNAS

Electronically scanned antennas have broad applicability for both commercial and military applications. Currently phased array antennas are utilized in advanced military radars, cellular base stations, some satellite communications applications and other such systems. Future uses include automotive anti-collision radar and improved wireless communications. Allowing an antenna to scan electronically has many benefits including fast scanning, the ability to host multiple antenna beams on the same array, eliminating mechanical complexity and reliability issues, the ability to angle the antenna in such a way that it reduces radar cross section for stealth reasons and the ability to operate over a wider frequency range. Phased array antennas typically consist of individual elements that are essentially each little antennas on their own.




**Sample Electronically Scanned Antenna Array**

Numbers of these elements are arrayed in a pattern depending on the desired performance characteristics needed by the application such as operating frequencies, antenna gain, sensitivity, power requirements, etc. Each element typically requires a phase shifter that applies a phase shift to that element based upon the desired beam scanning angle commanded by the system. The diagram below depicts how different phase shifts are applied to elements across an array to electronically steer the beam.



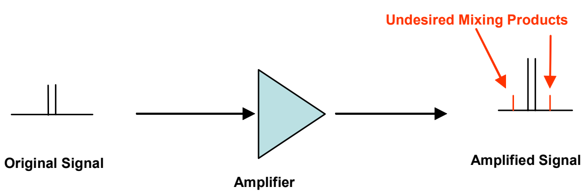

**Electronically Scanned Phased Array Antenna**

In the preceding diagram the phase shifters apply a different phase shift to each element in order to steer the beam. The shifted phase of each element causes the waves to interfere constructively giving the maximum gain in the desired direction. By simply commanding different phase shifts to the various elements across an array the beam can be steered very rapidly as opposed to mechanically scanned antennas. Additionally, depending on the antenna design, multiple beams can be formed and controlled simultaneously from a single array.

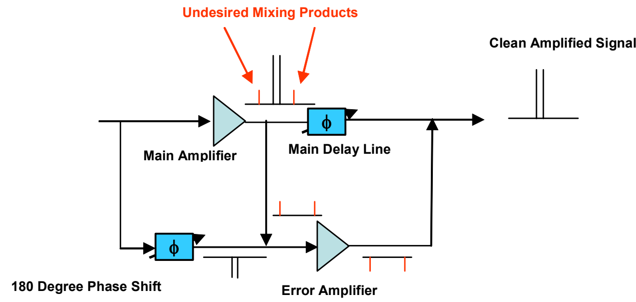
Phased array antenna systems have potentially many, many applications that could be realized if it is possible to reduce the cost of manufacture. With the high cost of the phase shifters themselves being such a significant portion of the overall antenna cost, any substantial reduction in the cost of phase shifters will allow much wider deployment of phased array antenna systems.

### Linearization of Amplifiers

When a signal is output from an amplifier there are certain undesired mixing products that are generated by the amplification process that introduce noise into the system. It is highly desirable to filter these unwanted signals out of the system and leave just a cleanly amplified signal.




Phase shifters provide an interesting and elegant way to perform this function. Because phase shifters possess the ability to change the phase of a signal it is possible to sample the undesired harmonics and change their phase by 180 degrees. Signals that are 180 degrees out of phase cancel each other out. By using a feed forward technique, the out of phase signal is coupled into the system causing the undesired harmonics to be easily cancelled out of the circuit. This technique has been utilized for years but found limited use due to the high expense of the phase shifters required to perform the task.




Linearized Amplifier using Phase Shifters

A lower cost phase shifter has the potential to allow many more systems to take advantage of this technique and dramatically and cost-effectively improve the performance of their systems.

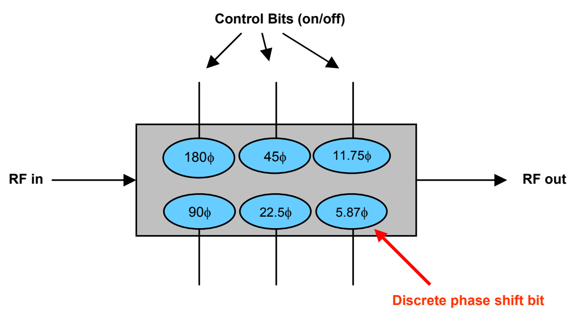
### Currently Available Solutions

There are a number of approaches utilized to design and produce phase shifters depending upon the application. For the purposes of this discussion we will focus on solutions that enable arrays to be developed that can employ standard commercial semiconductor manufacturing processes. By using standard commercial practices a manufacturer stands the best chance of using the economies of scale to produce an affordable product. There are basically two general methods of producing phase shifters: mechanical shifting and electronic shifting. Larger mechanical devices are expensive and can't take advantage of the economies of scale needed to make affordable phase shifters; therefore, the focus of this discussion will be on electronic phase shifters.

Electronic phase shifters that are manufactured using industry standard semiconductor manufacturing processes come in basically three flavors: *(1) Gallium Arsenide based digital phase shifters, (2) Micro-Electrical Mechanical System (MEMS) devices and (3) Ferroelectric based analog phase shifters.* Each of these technologies has their strengths and weaknesses, this paper will explore the trade-offs of each technology and how to arrive at the most cost effective solution to get the best performing phase shifters for the money.

## *Gallium Arsenide*

Gallium Arsenide (GaAs) based devices use an approach that employs a number of switches with differing delay values to achieve an aggregate phase shift. Each of these switches is biased either on or off giving it digital nature. A typical GaAs based phase shifter will employ a 5-bit control of the phase shift which yields discrete control of the phase shift in 11.75 degree increments, a 6-bit control would yield 5.875 degree phase control. The diagram below shows how a generalized digitally controlled phase shifter works:




Based on which bits are activated the total phase shift is additive. For example, if the 180 degree, 90 degree and 22.5 degree bits were turned on, the device would supply a signal with roughly a 292.5 degree phase shift. Depending on the application, digital phase shifting may present undesirable performance limitations if the resolution is inadequate. These GaAs phase shifters are typically very small, on the order of a few square millimeters, which make them a good candidate for thin-film semiconductor manufacturing processes. GaAs, on the other hand, is one of the most expensive semiconductor technologies to manufacture and generally requires special packaging during manufacture. The table below details the key strengths and weaknesses of the GaAs phase shifter:

**GaAs Phase Shifters**

| Strengths | Weaknesses |
|---|---|
| Very Small Size | Digital control requires multiple control lines and gives only discrete phase changes |
| Reliable, proven technology | GaAs is an expensive semiconductor process |
| Fast Tuning Speed | Consumes power |
| Good Tunability | Typically requires hermetic packaging |
| | Limited Power Handling |
| | Moderate RF Loss, generally requires Low Noise Amplifier |

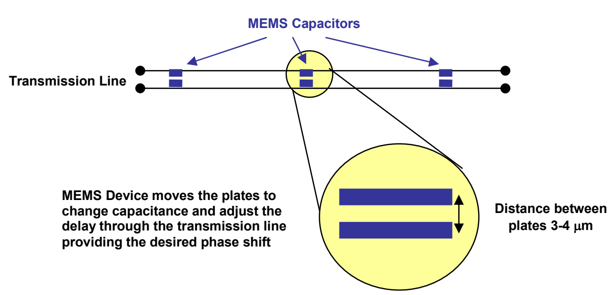
## *MEMS*

MEMS technology has received a lot of attention in recent years due to the promise of extremely low loss components and lack of undesirable intermodulation distortion. MEMS are essentially extremely small mechanical devices that can be manufactured using semiconductor manufacturing techniques. In the case of a phase shifter these devices would physically reshape the circuit to provide the desired phase change. In MEMS based phase shifters the phase shift is typically provided by using a delay line technique. The amount of phase shift is controlled by the amount of delay provided in a circuit. This delay is created by using MEMS capacitors which change their capacitance value based upon the physical movement of the miniature parallel plates which form the capacitors. Capacitance is produced by charging parallel plates and the amount of capacitance is a function of the parallel plates area and distance apart. By providing more capacitance in a delay line the amount of delay is increased and hence the phase shift. The formula below shows the relationship:

$$\Delta \phi = \omega \sqrt{L\left(C + C_d\right)}$$

Where $\Delta\phi$ is the phase change, $\omega$ is the frequency, L is the inductance, C is the fixed capacitance and $C_d$ is the variable capacitance provided by the MEMS capacitors. By this equation it is seen that the phase change is controlled by variable capacitance. The drawing below shows a depiction of a MEMS phase shifter:

One of the great attractions for MEMS devices is



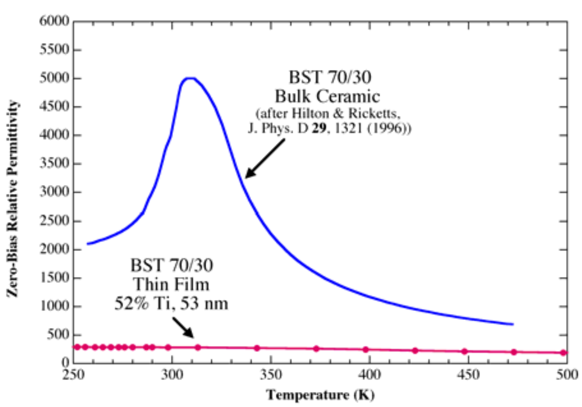

they are expected to be very low loss devices since the moving plates in the capacitors should deliver very high quality capacitors. In practice, they do demonstrate some excellent loss characteristics but the reliability of these miniature mechanical devices has proven to be very low. Significant effort is being expended to improve the reliability of MEMS devices in general and it is possible that they will mature in the years ahead but currently there are not any commercially viable devices on the market. The table below shows the strengths and weaknesses of current MEMS phase shifters:

**MEMS Phase Shifters**

| Strengths | Weaknesses |
|---|---|
| Fairly Small Size | Reliability is currently poor |
| Low RF Loss | Tuning speed is relatively slow due to mechanical movement |
| Wide tuning range provided by mechanical tuning | Consumes some power |
| Good Power Handling | Hermetic or other special packaging may be required |
| | High Control Voltages |
| | Cost is a possible issue, requires many layers of individual thin-film semiconductor processes |

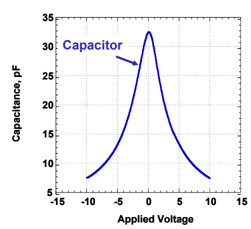
## *Ferroelectric Phase Shifters*

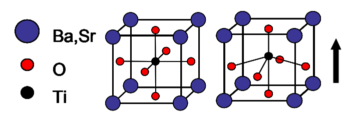
Ferroelectric materials are ceramic compounds that have unique dielectric properties and a very high capacitance density. In other words, large value capacitors can be constructed in a very small physical area. Bulk Ferroelectric, or thick-film, materials have been used for many years for such things as large industrial capacitors. Some work has been performed using thick-film ferroelectrics for phase shifters in a ferroelectric lens configuration, but that has yet to yield a commercially viable product and they have the unfortunate property of requiring very large control voltages, on the order of 1000's of volts, in order to achieve large phase changes. Thick-film ferroelectrics also have highly non-linear behavior with temperature change which makes them difficult to control precisely. The figure below compares thick and thin-film ferroelectric materials relative to temperature change:




From the preceding chart it is seen that thin-film ferroelectric material has very different properties from bulk or thick film material including a very flat temperature response profile giving thin-film ferroelectric material good controllability over wide temperature ranges. Thin-film ferroelectric material does maintain a very high capacitance density which makes it a good material for many applications. The difficult challenge of thin-film ferroelectrics comes in controlling the growth or deposition of the material during manufacture. If good material is grown on wafers then it is possible to construct high performance phase shifters.

Unlike MEMS, which requires the physical mechanical movement of the capacitor plates, thin-film ferroelectrics require only a voltage change to adjust the capacitance. The capacitance changes simply by the movement of atoms within the material making a capacitance change nearly instantaneous. The diagram below shows how the capacitance changes with voltage in the thin-film ferroelectric material BST, or Barium Strontium Titanate.

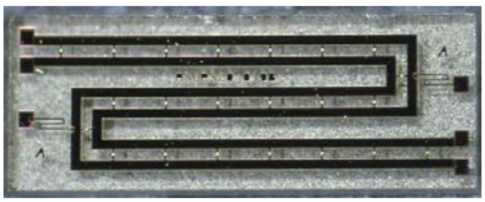



**Applied voltage cause the Titanium atom to move within the Octahedron which changes the capacitance**

This unique property of changing the capacitance with applied voltage gives the material the ability to tune the capacitance over a fairly wide range, at least a 2:1 change. Because the material has an extremely high capacitance density, very small tunable capacitors can be made which allows many thousands of them to be constructed on a single wafer. These tiny capacitors can also be used in a voltage controlled delay line to make phase shifters in the same manner as MEMS capacitors. By simply applying a control voltage to the phase shifter the amount of phase shift is controlled. BST also has an interesting property that results in increasing capacitor Q with increasing control voltage. Capacitor Q is a measure of a capacitors quality and is essentially a ratio of energy stored to energy wasted. Since the

Q increases with tuning voltage, the loss through the phase shifter decreases with increasing phase shift. The result is the loss at 360 degrees of phase shift is less than zero degrees of phase shift, generally the loss decreases by about half. This property results in improved power density of the scanned antenna beam at large scan angles off boresight, improved power density results in improved sensitivity of the antenna at large scan angles The following picture shows a phase shifter that was constructed using BST capacitors. This picture is of an actual phase shifter using a delay line configuration with a number of BST capacitors providing the delay.



The size of this device is only a few square millimeters. The table below shows the strengths and weaknesses of thin-film ferroelectric phase shifters.

**Thin-Film Ferroelectric Phase Shifters**

| Strengths | Weaknesses |
|---|---|
| Very small size | New technology |
| Good tunability | Needs more reliability data |
| No power consumption | Difficult to produce consistent high quality films |
| Analog tuning provides fine control and a single control line on the circuit board | Moderate RF loss, generally requires Low Noise Amplifier |
| Very fast tuning speed | |
| Low Cost, uses minimal number of standard thin film semiconductor processes | |

## Conclusions

The electronically scanned phased array antenna market is in desperate need of affordable phase shifters. Nearly half the cost of an array can easily be consumed by phase shifters. Using commercial semiconductor processes is the key to reducing the cost since many thousands of phase shifters can be manufactured on a single wafer which brings their cost down significantly. Newer technologies such as MEMS and Thin-Film Ferroelectrics have the potential to dramatically change the market as they mature. Thin-Film Ferroelectrics is very simple by nature and thus a less risky proposition than MEMS, additionally significant advances in Thin-Film Ferroelectric based phase shifters has been made in recent years. Gallium Arsinide is the most mature technology yet is more expensive.

**About Agile Materials and Technologies**

Founded in 1999, Agile Materials and Technologies the technology leader in tunable wireless components that enable commercial and military RF communications manufacturers to significantly decrease the number of components required for multi-mode systems, reducing device size, power consumption, complexity and cost. The company evolved from a Defense Advanced Research Project Administration (DARPA) funded research project on Frequency Agile materials (FAME) at the University of California, Santa Barbara, and has successfully commercialized its proprietary method to harness the unique properties of a thin-film ferroelectric material called Barium Strontium Titanate (BST). Unlike GaAs, MEMS, or thick- film technologies, Agile's technology facilitates the design and fabrication of high-performance tunable components that for the first time cost-effectively allow a single wireless device to operate over a range of frequencies and formats.

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