INVESTIGATION OF USING FERROELECTRIC MATERIALS IN HIGH POWER FAST RF PHASE SHIFTERS FOR RF VECTOR MODULATION*

Joshua L. Wilson, ORNL, Oak Ridge, TN, USA
Yoon W. Kang, ORNL, Oak Ridge, TN, USA
Aly Fathy, University of Tennessee, Knoxville, TN, USA

Abstract

A fast ferroelectric phase shifter controlled by an electric field bias is being investigated for high-power fast RF phase shifters to be used for vector modulation. Such a device could find applications in particle accelerators, allowing vector control of the RF power divided and delivered to accelerating cavities from a power amplifier. Bulk ferroelectric materials, particularly those based on barium-strontium titanate (BST) compounds, have shown promise in high-power applications because of their low loss tangent and high dielectric strength. Use of BST compounds is investigated in a coaxial phase shifter prototype for frequencies in the 400 MHz – 800 MHz range that could be adapted for future large-scale accelerator projects. Designs of subsystems such as the DC block and matching structure are discussed. Since BST is a nonlinear dielectric compound, preliminary study on the nonlinear propagation effects is also conducted through computer simulation.

BACKGROUND

Currently, to obtain continuous amplitude and phase control of the signals at the input of the accelerator cavities, separate klystrons are used to drive each cavity, so that control can be done at the low power input of the klystrons. This scheme is not ideal, since each klystron is capable of providing enough power for many cavities. The vector modulator will allow the control to be done at the high power side, so that fewer klystrons are needed, reducing overall system cost.

Several vector modulator topologies are possible. One scheme could employ a quadrature hybrid and two phase shifters. Another could use a stub network with any number of phase shifters on each stub, as in Figure 1 [1].

TUNABLE MATERIALS

At the heart of each of these schemes is a set of phase shifters that must be able to handle high peak and average power while maintaining fast response. These phase shifters employ materials that can be electrically tuned by one method or another. It should be noted that any transmission type phase shifter can be easily converted to a reflective type phase shifter by terminating one port with an open or short circuit.

*This work was supported by SNS through UT-Battelle, LLC, under contract DE-AC05-00OR22725 for the U.S. DOE.

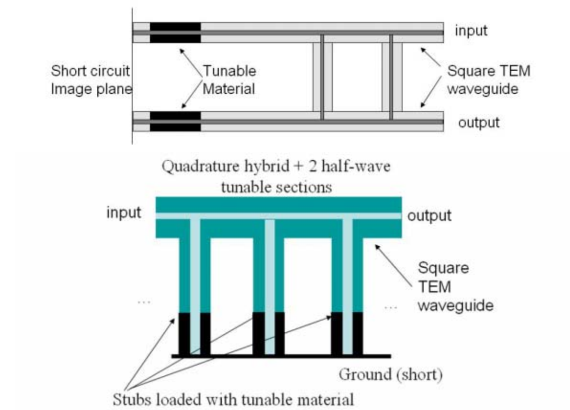

Figure 1: Vector modulator topologies.

Several different tunable materials have been investigated for use in accelerators. Ferrite materials have been used to achieve reasonably fast tuning [2]. However, the speed of any ferrite phase shifter is limited by how fast one can change the magnetic bias field within the ferrite. To accomplish fast tuning, solenoids with very few turns must be used with a very high current supply to change the bias field (and hence the phase) quickly.

Ferroelectric materials such as BST have also been used successfully in tunable accelerator structures at X-band frequencies [3]. Ferroelectrics change their electrical permittivity nonlinearly as a DC bias field is applied. Our prototype ferroelectric phase shifter demonstrates that tuning with BST is also possible at lower RF frequencies.

DIELECTRIC CHARACTERIZATION

Characterizing the BST dielectric is a necessary step in designing a phase shifter. The electrical characteristics of thin films of BST have been widely tabulated in many publications. However, the thin film characteristics of BST have been shown to differ significantly from the bulk characteristics [4]. The properties are also dependent on the exact fabrication process.

Measuring the permittivity and loss tangent of bulk BST presents a unique set of challenges. Since the relative permittivity of BST can be high (over 1,000) the experimenter must be cautious to avoid the onset of higher order modes in the measurement structure.

A number of methods were used, including the cavity detuning method, the loaded coaxial line method, and capacitor measurements. The capacitor method and coaxial loaded line method yielded similar results, while the cavity method was not as well suited for measurements of high-permittivity materials. The BST capacitors consisted of square plates roughly 0.5" X 0.5" X 0.05" coated in conductive epoxy. These dimensions were chosen to be large enough that thin-film effects would be negligible, yet small enough to ensure that resonance would not occur. At 400 MHz, the permittivity of our BST with 60/40 Ba/Sr ratio was measured to be 1157, while that of 30/70 Ba/Sr was 445. Measurements with a loaded coaxial line determined the permittivity of the 60/40 Ba/Sr to be 1075. This composition was also measured to have a loss tangent of 0.015.

MATCHING STRUCTURE

Since the permittivity of the BST is so high, a matching problem exists between the BST loaded section and the polyethylene loaded sections of the phase shifter. One possibility for creating a ferroelectric phase shifter would be to use a section of BST that is one half wavelength long, since good transmission should occur due to the "half-wave window" effect.

There are two problems with such an approach. First, since the difference in characteristic impedances is so great (roughly 6.19 ohms in the BST section and 50 ohms in the rest of the structure) the resonance that occurs will be extremely narrow, so the design frequency would have to be precise, and manufacturing tolerances kept very tight. Secondly, the lack of a matching structure around the BST would create a high VSWR in the lossy BST material, adding to the overall insertion loss of the phase shifter.

At the cost of making the structure slightly longer, a quarter wave alumina match (er = 9.8) can be added to each end of the BST section. Although a material with higher permittivity may theoretically yield a better match, alumina was chosen because it has extremely low loss and is readily available. The HFSS simulation in Figure 2 reveals the advantages of using such a matching structure, namely lower insertion loss (S21), better return loss (S11), and broader bandwidth.

The BST/alumina match was tested independently to ensure the accuracy of the HFSS solutions. For these tests, the 60/40 Ba/Sr composition was used, due to its higher tunability. A 0.9" square TEM waveguide with a 0.25" square inner conductor was loaded on top and bottom with two 0.25" X 0.325" X 1.25" BST bars. This was surrounded by a 2" long alumina matching structure, while the rest of the structure was loaded with polyethylene dielectric (50 ohm characteristic impedance). No dc bias was applied in this measurement.

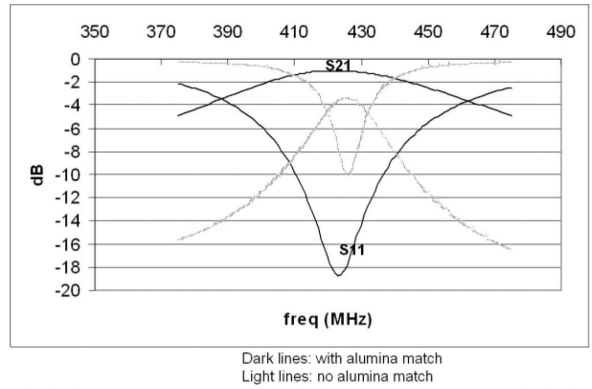

Figure 2: Alumina match performance.

A network analyzer was used to measure the scattering parameters, which were then compared to HFSS (see Figure 3). Overall, measurements were close to predicted results with a slightly higher return loss present in the measurements, possibly due to other transitions in the system.

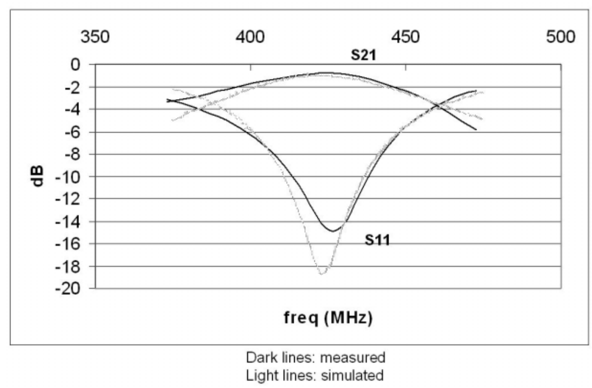

Figure 3: Alumina match measurement.

DC BLOCKS

The conventional DC block employing quarter-wave coupled-lines (Figure 4 (a)) performs rather poorly in our system (roughly 1 dB insertion loss). This is because the two lines have to be kept roughly 0.2" apart to achieve adequate DC insulation. A solution was found by placing the two blocks one half wavelength apart (Figure 4 (b)). While this causes higher VSWR on the BST section resulting in higher loss, it also results in an insertion loss of only 0.06 dB due to the block itself. This requires that the total electrical length of the line between the blocks, including the BST and match, is an integer multiple of one half wavelength. A two stage block, shown in Figure 4 (c) has been investigated theoretically, and shows good promise for future work.

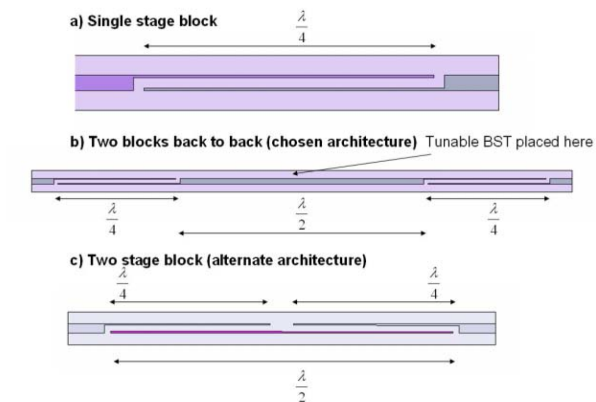

Figure 4: DC blocks.

EXPERIMENTAL RESULTS

Combining the BST, match, and DC blocks, one obtains the phase shifter prototype shown in Figure 5.

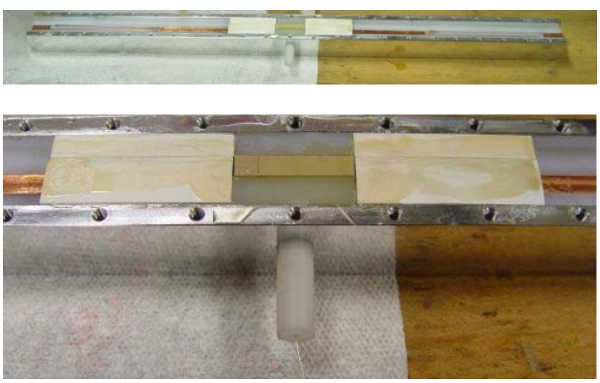

Figure 5: Prototype phase shifter showing BST bar (center) surrounded by two alumina matching sections with hole in center for DC feed.

DC bias is injected via a hole in the outer conductor in a location where the RF electric field is minimal, to avoid perturbation of these fields. To test the phase shifting capability, a variable high voltage DC (0 to 2500 V) was applied. Good transmission was observed at 468 MHz. The results are shown in Figure 6.

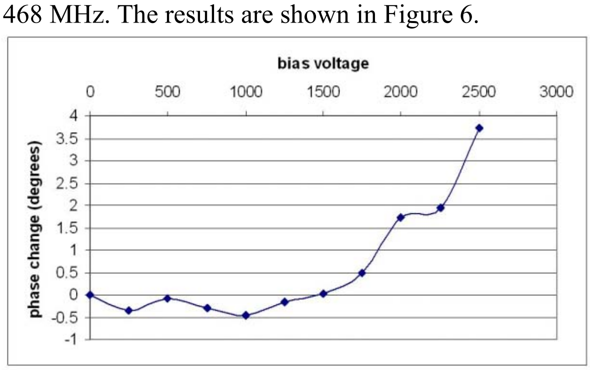

Figure 6: Observed phase change at 468 MHz.

The DC bias is done through a very thin wire connected to the inner conductor. The inductance of this line is further augmented by a small air-core inductor (roughly 13 μH) just outside the structure. The voltage was limited to 2.5 kV because of arcing in the structure, but with proper care (ensuring no air gaps are present), the structure could operate at voltages of 50 kV or higher.

NONLINEAR CHARACTERIZATION

BST and other ferroelectrics, because of their nonlinear permittivity, present an interesting problem in wave propagation, particularly at high power levels.

The nonlinearities are of a different nature from those encountered in ferrite structures, so careful analysis must be done. Because the only stable solutions to the nonlinear transmission line problem are solitons, one would expect a sinusoidal signal to distort eventually. A sample output from a Finite Difference Time Domain (FDTD) simulation implemented in MATLAB is shown in Figure 7, showing distortion in a semi-infinite BST-loaded line over several wavelengths. Although not an immediate concern for our system, one must be aware of the potential for harmonic distortion caused by this effect.

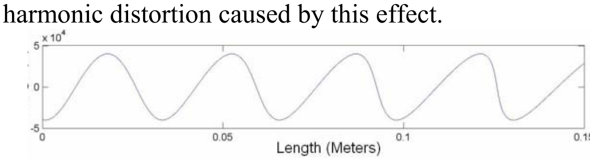

Figure 7: FDTD simulation of the nonlinear line.

CONCLUSION

A prototype BST-based coaxial-type phase shifter has been demonstrated at 468 MHz. Such a design could easily be scaled up or down to function at a wide range of desired frequencies. Such phase shifters show promise for use in future large-scale accelerator projects for reducing the number of necessary klystrons and cutting cost.

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