INVESTIGATION OF FERROELECTRICS FOR HIGH-POWER RF PHASE SHIFTERS IN ACCELERATOR SYSTEMS*

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Abstract

High power vector modulators enable independent control of radio frequency (RF) power to each accelerating cavity, allowing a fan-out configuration to be used to power many cavities from a single high-power klystron. Previously, ferrite materials have been used in high-power phase shifters and vector modulators. It is shown that ferroelectric materials such as barium-strontium titanate (BST) can also be used in such tunable structures. Since ferroelectrics are controlled by an electric, rather than a magnetic field, tuning can be faster than tuning a ferrite-loaded device. A BST-loaded coaxial structure is investigated theoretically and experimentally. The prototype is built using dielectric loaded TEM transmission line in order that no vacuum should be necessary. Good high voltage performance is critical since DC biasing voltages of up to 80 kV can be impressed on the BST sections for tuning. It can also be seen that matching structures around the BST can improve performance over a wider range of amplitudes and phases.

BACKGROUND

A good deal of research has already been performed on fast, high power phase shifters for accelerator applications. Reasonably fast waveguide ferrite phase shifters have been prototyped and tested successfully [1]. TEM ferrite phase shifters offer advantages, including very low loss at microwave frequencies and relatively simple biasing using a solenoid outside the structure. The main disadvantage is that eddy currents in the metal walls of the phase shifter and solenoid inductance tend to limit the tuning speed of ferrite phase shifters.

Ferroelectric materials such as BST have already shown great promise in fast high-power phase shifters [2]. Ferroelectrics are tuned by applying a bias electric field. In general, the permittivity decreases nonlinearly as the magnitude of the bias field is increased.

LOW POWER PROTOTYPE

A low power prototype, shown in Figure 1, has already been developed and tested [3]. A phase shift was observed at a frequency of 468 MHz.

For this design, two quarter-wave DC blocks were used, and the bias electric field was introduced by superimposing a high voltage on the center conductor of the coaxial line. An alumina matching transformer was used around the structure to effectively match the low characteristic impedance of the ferroelectric material to the 50-ohm system impedance.

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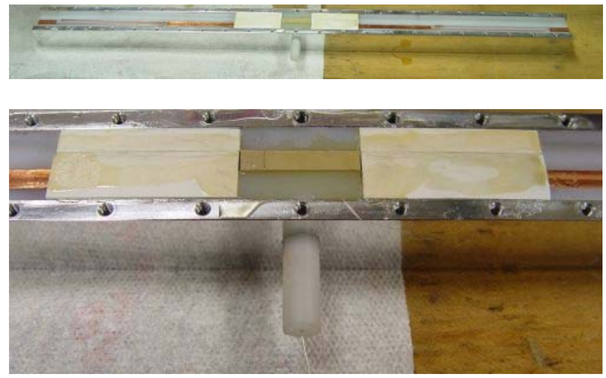

Figure 1: Prototype phase shifter showing BST bar (center) surrounded by two alumina matching sections with hole in center for DC feed.

The phase shift was rather small, as the bias voltage in this prototype was limited to 2.5 kV because of limited insulation in the structure. The phase shift as a function of applied bias voltage is seen in Figure 2.

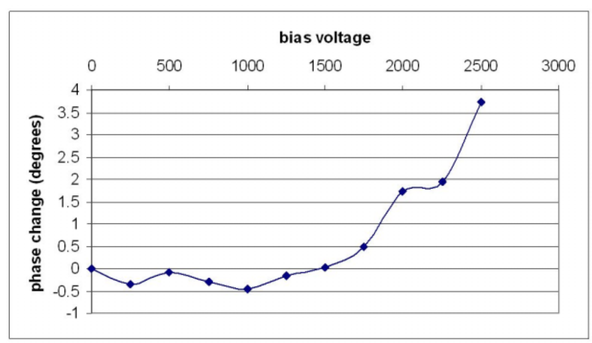

Figure 2: Phase shift at 468 MHz versus applied bias voltage in volts.

A great deal was learned from the experience with the low-power prototype. First, it is important to choose a low loss material, since the losses in the initial prototype were still too high for practical use. Secondly, great care must be taken to ensure that there are no air gaps within the polyethylene-based dielectric, since this severely limits the maximum voltage that can be applied. Finally, the DC block employed in the prototype could be significantly improved by switching from a quarter-wave design to a half-wave design, as will be discussed below.

To address these issues, a new prototype is currently being developed and fabricated. A new ferroelectric composition is being employed, which has already shown great promise in accelerator applications. [4] Also, in the first prototype a square inner conductor was used, and the structure was loaded with rectangular polyethylene bars. Although this provided low cost manufacturing, it also prohibited high bias voltages to be applied due to the small spaces between the bars. The new prototype is designed with a cylindrical inner conductor wherever possible, so that a single machined plastic piece can be used as insulation without any air gaps.

MATERIAL SELECTION AND GEOMETRY

BST material can have different compositions based on the ratio of barium to strontium in the compound. Increasing barium content provides higher tunability at a cost of higher loss.

Since almost any BST material tends to have a high permittivity (anywhere from 500 to over 1000), higher order modes may have a tendency to propagate within the phase shifter. Ideally, an incoming transverse electromagnetic (TEM) wave would not excite such modes, but in any real, physical system, imperfections could allow coupling to these modes. The field pattern for the unwanted mode with the lowest cutoff frequency is shown in Figure 3.

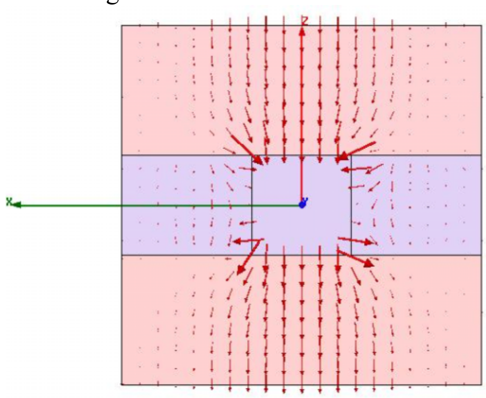

Figure 3: Higher Order TE mode in a Square TEM waveguide loaded with BST bars on top and bottom of the inner conductor.

This field resembles the TE10 waveguide mode. However, by reducing the width of the BST bars, the cutoff frequency of this TE mode increases, which can be used to damp the higher mode or altogether eliminate it. In the prototypes being developed, EM simulation was employed to choose the width of the BST so as to have no such higher modes.

MATCHING STRUCTURE

Since the relative permittivity of the BST ferroelectric material is high, a severe matching problem exists between the BST-loaded section of transmission line and the rest of the coaxial structure. In many cases, where the impedance mismatch is not too great, it is sufficient to simply use a half wavelength of tunable material without a special matching section surrounding it [5].

In the case of BST, a separate matching section is essential because the mismatch is very large. The BST section has an impedance close to 6 ohms, while the rest of the system has 50-ohm impedance. In the absence of a match, the resonant peak becomes very narrow, so the tunable range of the modulator is lessened. Also, the lack of a good match causes a high standing wave ratio in the BST, increasing the total field energy stored in the BST section and hence increasing the loss.

Two alumina sections were placed on either side of the BST. The alumina match has a characteristic impedance of roughly 24 ohms. Although this is slightly higher than the optimal impedance for this quarter-wave match, the alumina match offers advantages of very low loss and good availability. A comparison between a BST-loaded line with and without a match is shown in Figure 4.

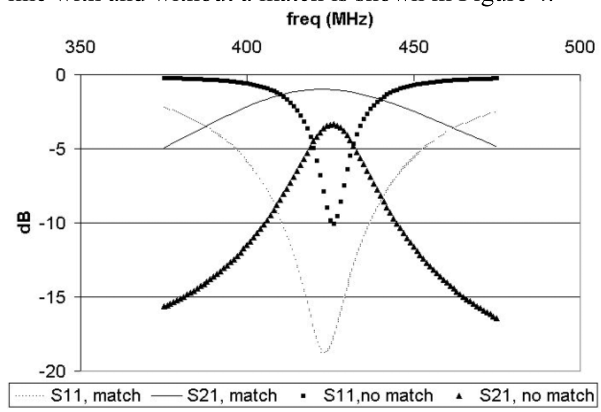

Figure 4: Simulated match performance with and without alumina match.

The scattering parameters were measured using a vector network analyzer. The measurements were taken in the absence of any DC bias network or DC blocks. The line was loaded with two 1.25 by 0.25 by 0.25-inch sections of BST of relative permittivity 1100. These data were then compared to High Frequency Structure Simulator (HFSS) simulations (see Figure 5). These calculations have been carried out using HFSS version 10.0 [6]. Overall, the measurements were in good agreement with simulation, with only slightly higher losses present, possibly due to other transitions in the system.

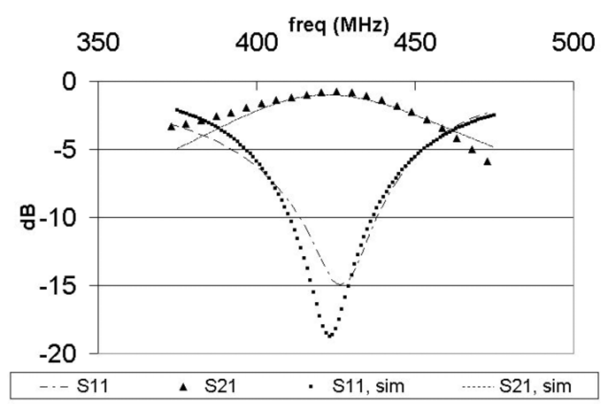

Figure 5: Alumina match measurement.

DC BLOCKS AND FEED

In order to bias the center conductor to a high voltage for tuning the BST, it is necessary to isolate a section of the center conductor of a transmission phase shifter using a pair of DC blocks, so that no DC will be seen at the two RF ports of the phase shifter. (For a reflective phase shifter, only one block would be needed.)

Since DC block capacitors typically do not have the necessary voltage rating and capacitance necessary for this application, a custom 402.5 MHz DC block is being designed using λ/4 line sections that work as impedance inverters. Figure 6 shows the two hollow cylindrical inner conductor sections surrounding a λ/2 long conductor insulated with an alumina ceramic tube. This acts as a half-wave resonator at 402.5 MHz, providing very good transmission at this center frequency.

Figure 6: Cylindrical half-wave DC block.

DC bias can be applied to the inner conductor using a hole in the outer conductor in a location where the RF electric field is low. This is important to avoid perturbation of the RF fields, causing more return loss. To minimize the loading of the DC probe on the RF signal, a very thin wire is used for biasing, and the inductance is further increased by a small inductor (roughly 13 μH) located just outside the phase shifter.

EXPECTED PHASE SHIFTER PERFORMANCE

The simulated transmission for a phase shifter with the ferroelectric material described in [4] is shown in Figure 7. Very good transmission is seen to occur near 400 MHz (less than 0.1 dB insertion loss). By reducing the permittivity of the BST material by 15%, a phase change of roughly 42 degrees is expected.

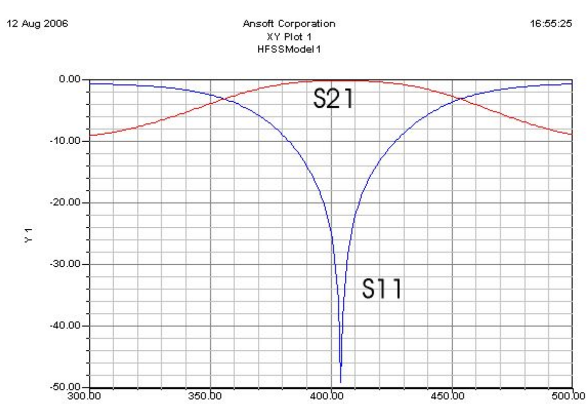

Figure 7: Simulated transmission for BST phase shifter (no DC bias).

CONCLUSION

A prototype BST-based coaxial-type phase shifter has been demonstrated at 468 MHz, and a new prototype is currently being developed in the 400 MHz to 500 MHz range. Such a design could easily be scaled up or down to function at a wide range of desired frequencies. These phase shifters require no vacuum systems, and show promise for use in future large-scale accelerator projects, cutting costs by reducing the number of klystrons necessary.

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