DEVELOPMENT OF HIGH-POWER RF VECTOR MODULATOR EMPLOYING TEM FERRITE PHASE SHIFTERS*

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Abstract

Construction and installation of a cavity radio frequency (RF) power distribution system in a high power superconducting RF accelerator can have cost savings if a fan-out configuration that feeds many cavities with a single high power klystron is realized. The configuration, however, requires independent control of RF amplitudes and phases to the cavities to perform properly. A prototype high power RF vector modulator for the control is built and tested. The vector modulator employs a quadrature hybrid and two fast ferrite phase shifters in square coaxial transverse electro-magnetic (TEM) transmission lines. The square coaxial format can provide the power handling capability and thermal stability. RF properties of the design and results of high power system testing of the design are presented.

BACKGROUND

Figure 1 shows the architecture of the modulator, consisting of a quadrature hybrid and two reflective phase shifters.

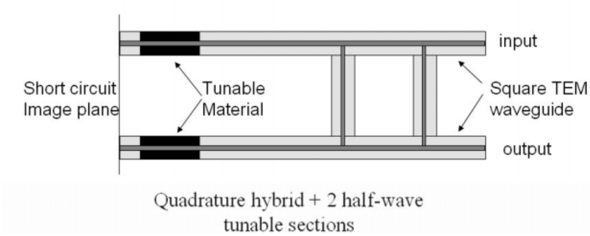

Figure 1: Vector modulator design with reflective phase shifters

The feasibility of a TEM mode vector modulator has recently been demonstrated at low power [1]. This research showed that by varying bias current through the two solenoids, a phase range of roughly 130 degrees and an amplitude range of 0.35 to 0.97 could be achieved, as shown in Figure 2.

Other high-power vector modulator designs have also been proposed and tested [2], one of them employing two reflective type phase shifters mounted to a WR-2300 waveguide [3].

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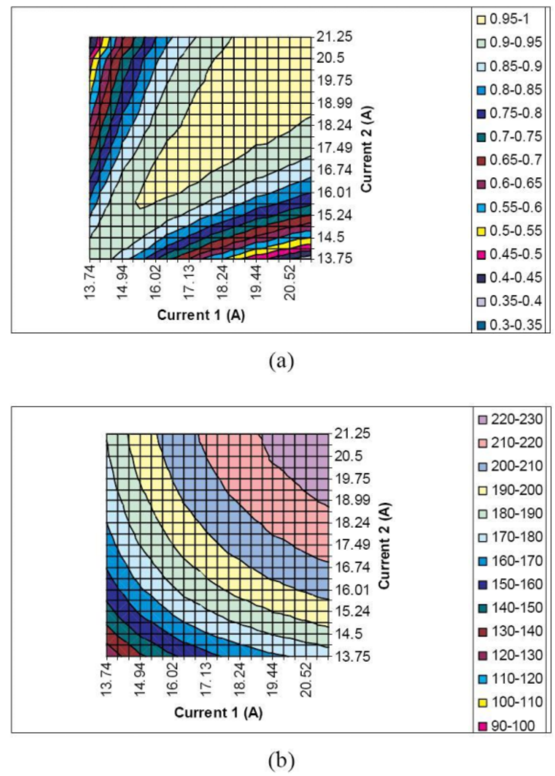

Figure 2: Measured control ranges of low-power vector modulator (a) amplitude (b) phase.

SYSTEM OVERVIEW

The entire prototype vector modulator structure is based on square coaxial TEM transmission line. The operating frequency for this prototype is 402.5 MHz, which is the frequency of the low-energy portion of the SNS Linac.

For a vector modulator system, the output voltage can be expressed in terms of the incident voltage and the phases of the two reflective phase shifters.

$$V_{out} = jV_{inc}\cos(\phi_1 - \phi_2)e^{j(\phi_1+\phi_2)}$$

The phases $\phi 1$ and $\phi 2$ above are the phase shifts of a signal transmitted one way through the phase shifter (one half of the total reflective phase shift). This expression leads to a linear relationship between the phases of the phase shifters and the output amplitude and phase. By independently controlling the quantities ($\phi 1-\phi 2$) and ($\phi 1+\phi 2$), the output can be driven to any desired amplitude and phase.

Realistically, the phases will both be continuously variable within a certain range. This will produce a control region in the amplitude-phase plane. For phase shifters capable of a 130-degree total reflective phase shift, this region is plotted in Figure 3.

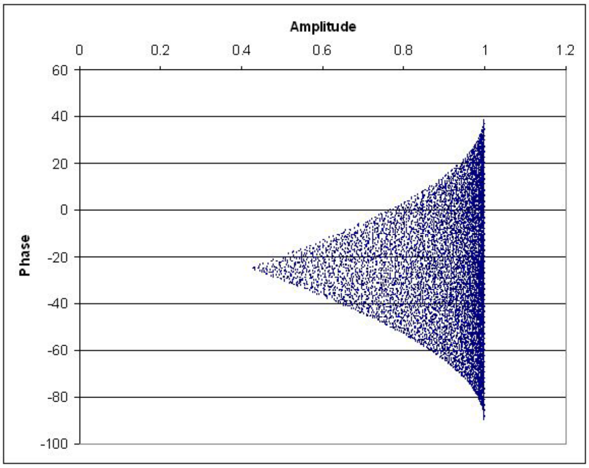

Figure 3: Expected control region in Amplitude-Phase space for 130-degree reflective phase shifters.

It should be noted that the topology of this region could be altered by adding fixed phase shifts to one or both of the phase shifters. This will not be discussed here, however, since this type of design decision will be considerably influenced by the particular application. In general, all of the power is not seen at the output of the vector modulator. The left-over power is reflected back to the input, where in most cases it is absorbed by a dummy load on a circulator.

FERRITE PHASE SHIFTERS

The active phase shifting element in the vector modulator is a gadolinium-doped garnet material. These materials are desirable for high-power applications due to their low loss tangent at microwave frequencies. The relative permittivity of the material is roughly 14. The effective permeability can be varied by applying a longitudinal magnetic bias field. It has been demonstrated that such ferrite phase shifters can exhibit fast tuning with less than 100 μs response time [4].

Since there is in general an impedance mismatch between the ferrite section and the rest of the structure, reflections must be avoided to ensure that the EM wave interacts with the ferrite material instead of being reflected at the ferrite interface. In this case, it is sufficient to choose the ferrite length as roughly one half wavelength to avoid the added complexity of a matching structure and still maintain good transmission. To go to extremely large phase shifts, it would be necessary to add a matching section on each side of the ferrite, but for most accelerator applications this would not be necessary.

A given length of ferrite will give good transmission for a range of bias currents at any given frequency. This, in turn, determines the maximum differential phase shift. Figure 4 shows bias currents and frequencies for which good transmission occurs for a ferrite length of 7.3 inches. The simulations were carried out in Ansoft High Frequency Structure Simulator (HFSS) Version 10.0 [5].

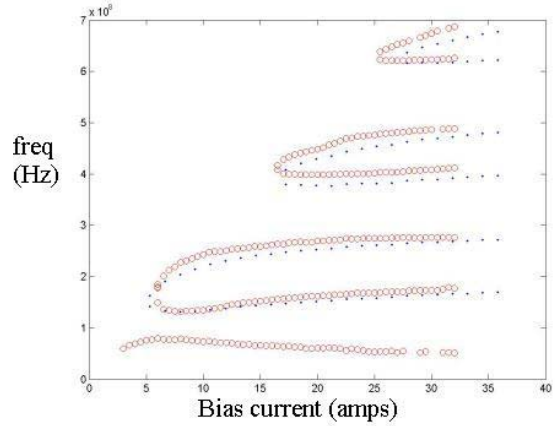

Figure 4: HFSS Simulated and measured regions for good transmission. Circles are simulated values; Points are measured values.

Using reflective phase shifters as opposed to transmission-type phase shifters offers the advantage that roughly twice the phase shift can be achieved. However, a reflective design also introduces a standing wave pattern into the phase shifter, which complicates the analysis slightly. This may also reduce the peak power handling capability of the system. The loss in the ferrite is related to the loss tangent and field distribution by

$$P_{dissipated} \propto \tan(\delta) \int_{length\ of\ ferrite} | I(l) |^2 dl$$

By varying the distance between the ferrite and the short in the reflective phase shifter, the standing wave pattern within the ferrite changes and the loss in the ferrite varies. In our design, analytic expressions as well as EM simulations and experimental results helped to optimize the position of the ferrite with respect to the short.

The ferrites in our design were operated on the high-field side of gyromagnetic resonance. This offers much lower loss at the cost of higher biasing currents. However, these biasing currents could be reduced by application of a static magnetic field (by a permanent magnet, for example) and then superimposing a tuneable bias field.

HIGH POWER DESIGN CONSIDERATIONS

The design in [1] has been altered in this prototype to allow high power operation. To facilitate this, it was necessary to provide a means to water cool the structure and to ensure that there are no breakdowns in the structure due to the high voltages associated with the high-power RF signal. The prototype structure is seen in Figure 5.

The phase shifters with the ferrite pieces can be seen on the right side of the hybrid in the diagram. The ferrite slabs were placed 3.85 inches away from the copper shorting plate, following the optimization procedure discussed above.

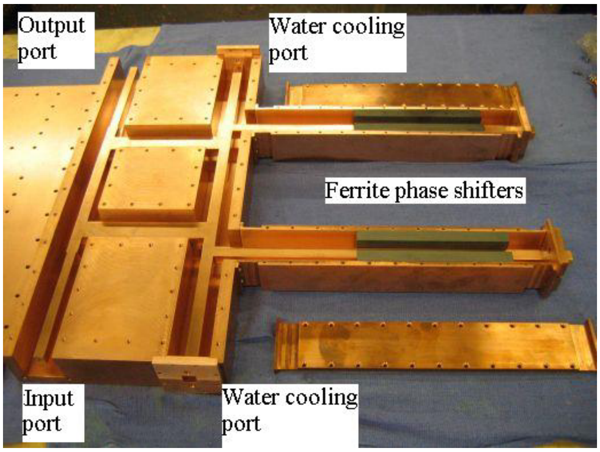

Figure 5: High power vector modulator prototype showing input and output port, water cooling port, and ferrite phase shifters.

The first major challenge to high-power operation is insulation breakdown. The outer conductor in this case is 1.5 by 1.5 inches. This large size increases the voltage handling capability. The vector modulator is to be loaded with polypropylene dielectric, which has very good dielectric strength, low loss tangent, and good mechanical properties. This has the advantage that no vacuum is necessary in the modulator. However, to ensure that there are no small air gaps between the polypropylene pieces that could cause arcing and damage to the structure, it is necessary to melt the plastic pieces together. Air gaps also had to be carefully prevented at all interfaces between the polypropylene and ferrite. All of the ferrite pieces were notched to facilitate this.

Another consideration for high-power operation is how to water cool the structure. To accomplish this, a larger inner conductor had to be used with a hollow center to allow the water to flow through. The water was routed through the structure via two quarter-wave short-circuited stubs. The larger inner conductor, however, also altered the characteristic impedance of the system to less than 50 ohms. To match the entire modulator back to a 50 ohm system impedance, a quarter-wave transformer was used at the input and output ports. The transformer was implemented by adding a step in the width of the inner conductor. The simulated response of the structure, not including the ferrite sections, is shown below in Figure 6. The expected insertion loss is roughly 0.015 dB.

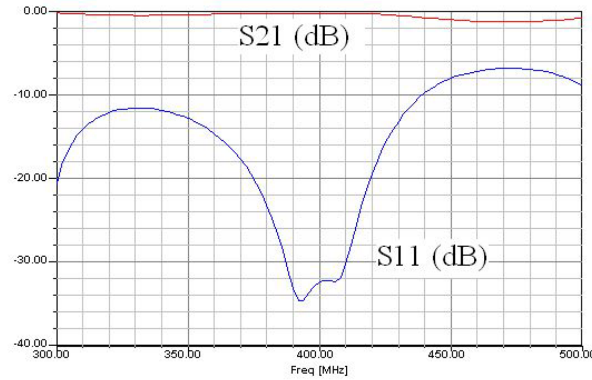

Figure 6: Simulated response of vector modulator, not including ferrite sections.

CONCLUSION

It has already been shown that high-power RF vector modulation near 400 MHz using ferrite phase shifters is feasible. Assembling and testing of a high-power prototype is in progress. The current vector modulator design does not require a vacuum for operation, and is capable of high peak and average power. This makes the vector modulator attractive for future large-scale accelerator projects.

ACKNOWLEGEMENTS

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[5] Ansoft HFSS. Version 10.0. Copyright © 1984-2005, Ansoft Corporation.