DEVELOPMENT AND TESTING OF HIGH POWER RF VECTOR MODULATORS*

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Abstract

A fan-out RF power distribution system can allow many accelerating cavities to be powered by a single high-power klystron amplifier. High-power vector modulators can perform independent control of amplitudes and phases of RF voltages at the cavities without changing the klystron signal. A prototype high-power RF vector modulator employing a quadrature hybrid and two ferrite phase shifters in coaxial TEM transmission lines has been built and tested for 402.5 MHz. RF properties of the design and results of high power testing are presented.

INTRODUCTION

Figure 1 shows architectures of some simple forms of a vector modulator for high-power operation, consisting of a single or two hybrid junctions and two phase shifters. Traveling waves exist in the phase shifters if two separate hybrids are used. Standing waves are used in the short circuited phase shifters if a single hybrid is used.

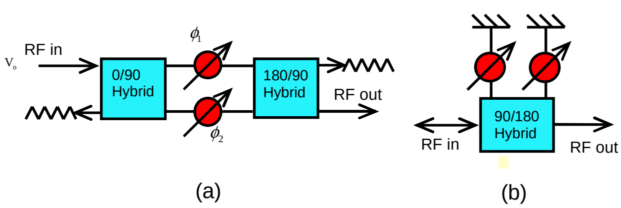

Figure 1: Vector modulator realization with (a) traveling and (b) standing waves in the phase shifters.

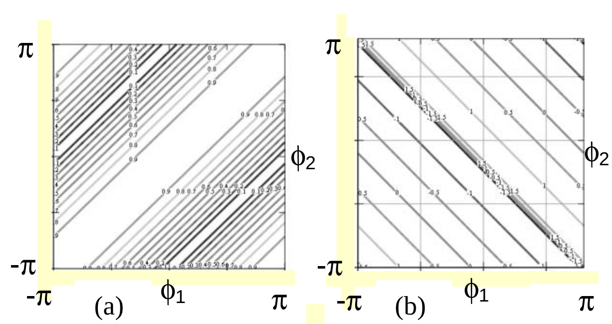

Figure 2: Vector modulator responses with respect to two phases: (a) amplitude, (b) phase.

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 two phases, ϕ_1 and ϕ_2 in the above are the phase shifts of a signal transmitted one way through the phase shifter. This expression leads to a linear relationship between the phases of the phase shifters and the output amplitude and phase. By controlling the quantities $(\phi_1-\phi_2)$ and $(\phi_1+\phi_2)$, the output can be driven to any desired amplitude and phase as shown in Figure 2. With the phases continuously variable within a certain range, a control region in the amplitude-phase plane will result. 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.

A high-power vector modulator in WR-2300 waveguide employing two reflective type phase shifters was reported [1]. Other high-power vector modulator designs have also been proposed and tested [2]. The design and construction of high- power TEM mode vector modulator has been investigated [3]. The entire prototype vector modulator structure reported in this paper is based on square coaxial TEM transmission line operating at 402.5 MHz, which is the operating frequency of the low-energy portion of the SNS linac. The design goal of the vector modulator is high power handling capability of up to 500 kW peak power at 8% duty cycle, and fast tuning with faster than 1°/µs response speed.

PHASE SHIFTER

The active phase shifting element in the vector modulator is a gadolinium-doped garnet ferrite 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 13. The effective permeability can be varied by applying a longitudinal magnetic bias field in a TEM mode design.

An impedance mismatch exists at the boundary of the ferrite section and the rest of the structure, so proper impedance matching is needed in order for the wave to interact 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. This approach is considered adequate for most high-power accelerator applications. In general, in order to have a large phase shift, it is necessary to add a matching section on each side of the ferrite and/or make the active length a multiple of one half wavelength.

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

1-4244-0917-9/07/$25.00

Figure 3 shows the measured phase and amplitude of a single coaxial phase shifter at low power. One end of the phase shifter is short circuited and a phase range of roughly 120 degrees was achieved by varying the solenoid bias current over the useful amplitude range.

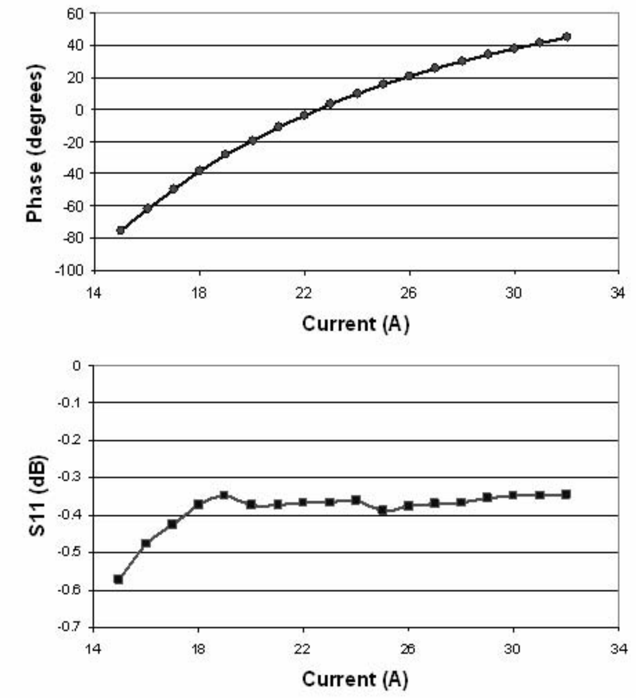

Figure 3: Measured control ranges of low-power vector modulator: (a) phase and (b) amplitude.

A given length of ferrite will give good transmission for a range of bias currents for a particular frequency. By varying the distance between the ferrite and the short in the phase shifter, the standing wave pattern within the ferrite changes and the reflection can be minimized. 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. This, in turn, determines the maximum differential phase shift. The simulations were carried out in Ansoft High Frequency Structure Simulator (HFSS) Version 10.0 [4].

VECTOR MODULATOR

A vector modulator using standing-wave type phase shifters as opposed to traveling-wave type phase shifters has the advantage that roughly twice the phase shift can be achieved. However, a reflective design also introduces standing wave peaks up to four times higher in power into the phase shifter region, which complicates the performance and may reduce the peak power handling capability of the system.

The design in [3] has been altered in this prototype to allow higher power operation with water cooling of the center conductor and to ensure that there are no breakdowns in the structure due to the high voltages associated with the high-power RF signal. Figure 4 shows the prototype structure with the ferrite slabs and the top covers removed. 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 shorted end, following the optimization procedure discussed above. In general, all of the power is not seen at the output of the vector modulator. The leftover power is reflected back to the input, where in most cases it is absorbed by a dummy load on a circulator.

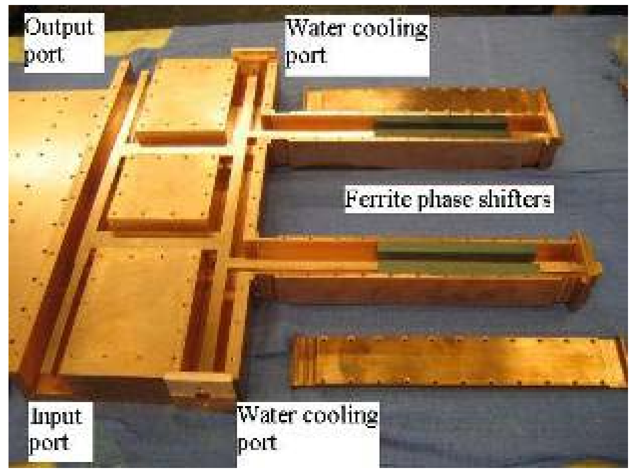

Figure 4: High power vector modulator prototype shows input and output port, water cooling port, and ferrite phase shifters.

The outer conductor in this case is 1.5 by 1.5 inches and is filled with polypropylene dielectric. Two λ/4 short stubs were added in the center conductor circuit to provide a water connection that is transparent to the RF signal. Dielectric loaded circular coaxial transitions are used to convert the square coaxial circuit to standard EIA type air-dielectric coaxial transmission lines.

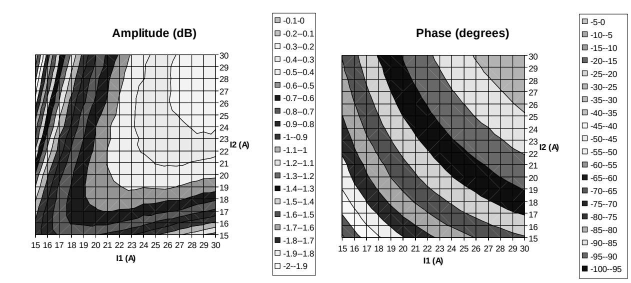

Figure 5: Low power bench measurements of the amplitude and phase of vector modulator using VNA.

For magnetic biasing of the phase shifters, a pair of solenoids was used temporarily with DC biasing. Figure 5 shows the results of low power bench measurement using a vector network analyzer. Note that in Figure 5 plots use magnet currents instead the phase shifts in Figure 2, revealing the nonlinear characteristic of the phase shifters.

HIGH POWER TEST

Figure 5 shows the setup for high power RF testing. A 402 MHz 2.5 MW Klystron was used with a -7 dB hybrid

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coupler for convenience. The forward and reflected power levels at the input and the output were monitored, and the amplitude and phase responses were measured at certain power levels.

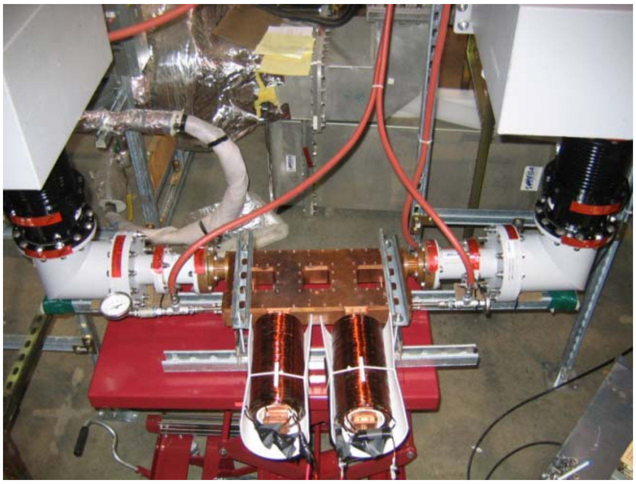

Figure 6: High power test setup with 402 MHz RF system for the vector modulator in the test facility.

The major goal of this test was to verify the high-power capability of a modulator with polypropylene dielectric insulator material, which has very good dielectric strength, low loss factor, and good mechanical properties.

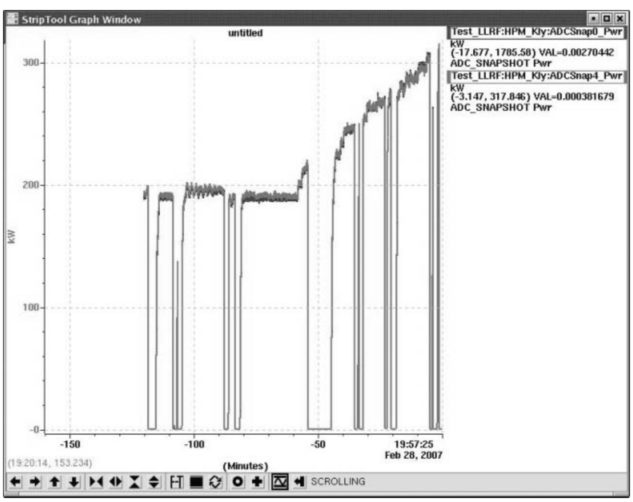

Figure 7: Power deposition to the vector modulator. Reached 385 kW peak power in 1 msec 30 Hz pulses.

To accomplish effective cooling of the structure during high power operation, a larger inner conductor had to be used with a hollow center to allow the water to flow through. The larger cross-section of inner conductor also altered the characteristic impedance of the system to slightly 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.

Figure 7 shows a profile of the forward power during the test. The maximum forward RF power reached 385 kW in 1 msec, 30 Hz pulses until the structure failed. The measured response of the modulator at 300 kW input power is shown below in Figure 8. This result was derived with a relatively small number of data points, spanning only the lower triangle of the rectangular control region and assuming symmetry in the I1-I2 plane. More precision measurements will be made in the future.

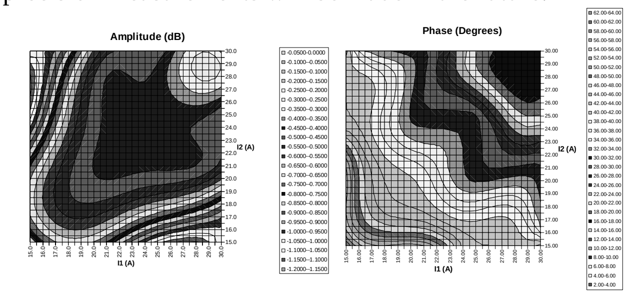

Figure 8: Measured amplitude and phase responses of vector modulator at 300 kW operation.

CONCLUSION

Results of construction and high-power testing of a prototype vector modulator for 400 MHz using coaxial ferrite phase shifters are presented. Delivering truly useful vector modulators is considered feasible but requires more work. Vector modulators have significant potential as RF control components in a fan-out RF system for future large-scale accelerators. The prototype vector modulator has been designed to demonstrate compactness at around 400 MHz, a relatively low RF frequency, while achieving high peak and average power capability. The solenoid magnetic biasing will be replaced with lower inductance ferrite yoke magnets for fast control with pulsed biasing. For higher power operation with high RF voltage insulation inside the structure, a single molded dielectric piece will be used.

ACKNOWLEGEMENTS

The authors thank Rob Peglow, Sydney N. Murray III, Jim Diamond, Greg Knox, and Max Cronan of SNS project for their contributions.

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