FAST RF FERRITE PHASE SHIFTER FOR HIGH-POWER APPLICATIONS

Y. Kang, Argonne National Laboratory, Argonne, IL, U.S.A.

Abstract

Fast rf phase shifters may be needed, in powering a superconducting linac, between rf generators and accelerating cavities when one klystron feeds more than one cavity. The configuration with one klystron for many cavities needs orthogonal controls of magnitude and phase of rf power in order to preserve system performance while reducing construction cost. For this reason, a waveguide ferrite phase shifter design was investigated to determine if the desired rf specifications can be satisfied: less than 100 μs response for about 80 degrees of phase shift. Results of the investigation into the rf properties of a waveguide phase shifter design and low-power bench testing are discussed.

1 INTRODUCTION

The first goal for the development of the fast waveguide phase shifter project was to show the response time and shifting range. Prototyping and testing of the phase shifter with low-power measurement became the focus of our efforts. The high-power device would be made after the step with low power testing was complete and if the phase shifters are necessary.

Table 1 shows the electrical specification of the phase shifters that may be adopted for a superconducting linac rf system of the Spallation Neutron Source (SNS) Project. The operating frequency range can be narrow and the insertion loss must be low to have low rf power dissipation in the phase shifter for reliable and efficient operation.

Table 1. Phase Shifter Specification For SNS

Frequency:	805 MHz ± 1 MHz
Insertion loss:	0.15 dB max
Input VSWR:	1.2 : 1 max
Phase shift:	0 ~ 80 degrees
Response:	< 100 μs
Peak power:	500 kW
Duty cycle:	8%

The requirement on the low rf insertion loss demands careful selection of the ferrite material. Since parallel biased soft ferrite material exhibits extreme rf power loss at frequencies higher than a few tens of MHz, orthogonal biased ferrite must be used. For this reason, a low loss yttrium iron garnet (YIG) ferrite material was selected for the project. The saturation magnetization, $4\pi M_s$ affects the power dissipation in the YIG material. An optimum ferrite can be selected for a frequency with the relationship [1]

$$0.2 < \gamma\, 4\pi M_s / \omega < 0.6,$$

where γ = 2.8 MHz/Oe (= 35 kHz/A/m) is the gyromagnetic ratio of the ferrite, and ω is the frequency of operation.

2 PHASE SHIFTER DESIGN

Orthogonal biased ferrite exhibits low rf loss when the material operates in a circularly polarized rf magnetic field that is orthogonal to the magnetic bias field. The system becomes nonreciprocal due to nonreciprocal tensor permeability. For the 805-MHz application, a low saturation magnetization less than 200 gauss with a low resonance line width is desired. This requirement can be satisfied with a commercially available YIG material but with a long lead time.

2.1 Orthogonal Biased YIG Ferrite

Several rf waveguide configurations are possible for the phase shifter construction. For high-power and high-speed applications, a two-slab design, shown in Figure 1, was chosen. The ferrite slabs are placed in a hollow waveguide where rf magnetic fields are circularly polarized in the plane orthogonal to the external magnetic bias field. Using the circularly polarized magnetic fields requires that the orthogonal biased ferrite slabs be located at around 1/3 and 2/3 of the width in the rectangular waveguide.

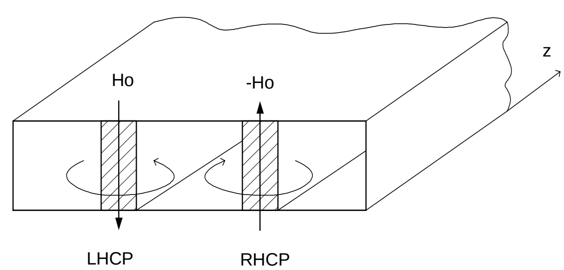

Figure 1: Two circularly polarized magnetic fields of a TE_{01} mode in a rectangular waveguide.

Figure 1 shows the magnetic field of the regular TE_{01} mode in a rectangular waveguide. The magnetic fields look like two opposite-directed circularly polarized waves inside the waveguide. The directions of the external magnetic bias fields are opposite each other so that both YIG slabs operate symmetrically.

For this project, readily available low loss YIG material slabs were acquired. The YIG material had the saturation magnetization $4\pi M_s$ = 250 Gauss and low spin-wave resonance line width. The material had a high dielectric permittivity with low loss (ε_r = 14 and *tan* δ = 0.00015). The slabs measured 2” x 6” x 0.5”.

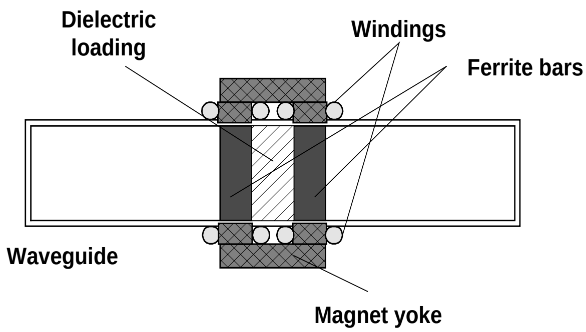

Figure 2. Cross section of a waveguide phase shifter.

The two-slab configuration allows use of two short magnets for biasing as shown in Figure 2. The fast shifting response of the phase shifter needs low inductance in the bias winding of the magnet. For reducing the inductance, the distance between the YIG slabs must be minimized while maintaining an adequate spacing for minimizing the bias field leakage. Dielectric loading can be used for this purpose [2]. For this prototyping, a 0.5”-thick (er = 9.8) alumina ceramic plate was used. Since a proper impedance matching around the YIG material and the dielectric slabs was required, a small step transformer made of alumina was used on each end of the ferrite slabs. A uniform 2” reduced height waveguide structure was used to construct the phase shifter.

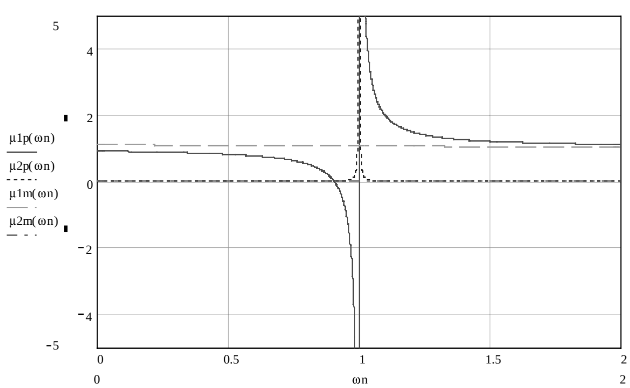

Figure 3. Complex permeability of a YIG material, $4\pi M_s$ = 250 Gauss, ΔH_k = 4 Oe, $\omega_n = \omega_o/\omega$.

Using a YIG material with saturation magnetization 4πMs = 250 Gauss requires a bias magnetic field H_o = ~ 18 kA/m for a range of ferrite permeability μ_r = 0.9 ~ 0.7 for operation below resonance. The effective magnetic path length of the magnetic circuit is ~ 0.15 m, and the required current is up to ~ 3 kA in the YIG. The external biasing field current may be lower with a higher permeability external magnet yoke since the magnetic flux normal to the interface is continuous.

Figure 3 shows the permeabilities of the orthogonal biased YIG material. μ^+ must be used since μ^+ varies with respect to the magnetic bias field H_o; the permeability $\mu^+ <$ 1, while $\mu^- \cong 1$. At resonance, ω_n = 1 and the magnetic field H_o = 23 kA/m.

2.2 Biasing Magnets

For the initial testing, Fair-rite 78 material was used to form ‘C’ shaped magnets. An available high-power pulse generator, which has a pulsed output of 1.5kV ~ 3A up to a few milliseconds, was used.

A magnetic field bias winding with an inductance L_s = 1 μH and a resistance R_s = 0.1 Ω will have half power frequency, $f_{-3\,dB}$ = 16 kHz. For rf shielding and magnet flux penetration, a thin metallic layer is needed at the boundaries of the external ‘C’ cores and YIG slabs. In the testing, aluminum foils were used. With the aluminum waveguide wall, one skin depth is 0.026” at *f* = 16 kHz. The eddy-current loss at the rf shielding will affect most for the slew rate of the phase shifter. Since the skin depth at 805 MHz is only ~ 3 μm in aluminum, thinner is better.

Table 2. Scalar Permeabilities of Materials Used in the Phase Shifter

Material	μ_r	Path length (m)
Magnet ferrite	~ 2000	0.12
YIG	~ 40	0.11
Aluminum	~ 1	0.0005

Scalar permeabilities of the materials for the phase shifter are shown in Table 2. Inductance of the magnet winding can be determined approximately. With the ‘C’ magnets, the YIG slabs within the 2” reduced height waveguide, and the foils, the effective relative permeability is estimated at $\mu_{r,e}$ ~ 71. Inductance of a single-turn magnet winding is estimated to be L_s ~ 0.95 μH. This inductance is confirmed from the measurement.

3 MEASUREMENT

Figures 4 and 5 show the construction of the phase shifter. Two coaxial-to-waveguide transitions are integrated to the waveguide with adjustable shorts. In the measurement, an rf signal is divided into two identical signals. A phase detector that is basically a double-balanced mixer is used to compare phases of the two signals: one direct as the reference and the second through the phase shifter under test. The phase detector converts the phase shift to a voltage output. The output voltage was measured with known phase shifts for reference prior to the pulsed measurement. The phase shift and insertion loss are shown in Figure 6.

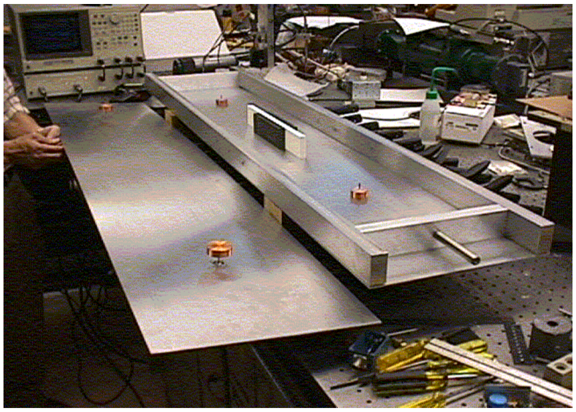

Figure 4. 2" height waveguide loaded with YIG and alumina slabs, and two coax-to-waveguide transitions.

Figure 5. Waveguide is shown with ferrite magnets with two coax-to-waveguide transitions and clamps.

Measured phase shifter response is shown in Figure 7. The input pulse voltage, input current, and phase detector output are shown. The output of the pulse power supply has very fast rise and fall time. A pulse transformer is used to obtain a higher current from the high voltage pulse generator.

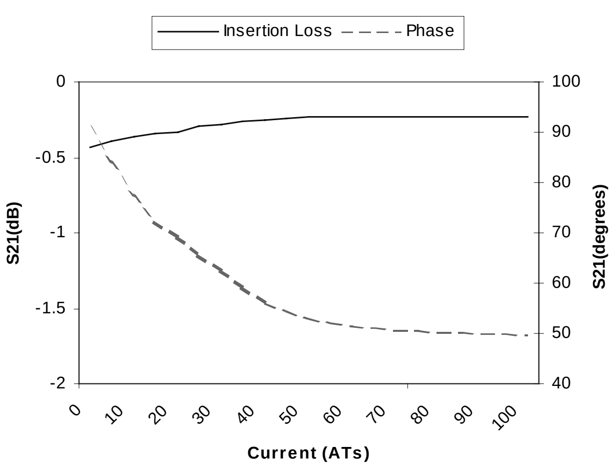

Figure 6. Measured phase shift and insertion loss vs. bias current.

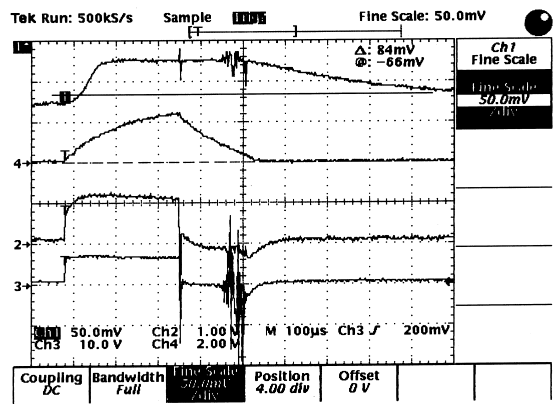

Figure 7. Measured phase shifter response. 1=phase detector output, 2=pulse transformer input voltage (x1000 probe), 3=pulse transformer output voltage, 4=phase shifter bias current (1 V for 100 A).

4 CONCLUSION

The phase shifter functioned as expected. It was housed in a 2" reduced height waveguide with a 9.75" width. A 6" section provided 40 degrees of phase shift at 805 MHz. An 80-degree phase shift must be obtained by using a 12" section. Higher energy biasing delivers faster phase shifting. The prototype showed that fast phase shifting is possible, with a ~ 30V and 300-A power source, for less than 50 µs response time. A new power supply design with a large bandwidth and a proper feedback control is needed for fast response. The rf shielding placed between the biasing magnets and the YIG slabs creates eddy-current loss that resulted in a slower response. Phase shift vs. the magnet bias current is not linear. Optimization of the external magnet design and bias magnet power supply is needed. For high power testing, cooling will be needed to protect the YIG ferrite.

5 ACKNOWLEDGEMENT

The author greatly appreciates the help of J. Tsai and T. Bigalow of Fusion Research Lab and R. Fuja and G. Johnson of the SNS Project at Oak Ridge National Laboratory. This work was supported by the U.S. Department of Energy, Office of Basic Energy Sciences, under Contract No. W-31-109-ENG-38.

REFERENCES

[1] W. E. Hord, "Design Considerations for Rotary-Field Ferrite Phase Shifters," *Microwave J.*, Vol. 31, November, 1988, pp. 105-115.

[2] W. J. Ince and E. Stern, "Non-Reciprocal Remanence Phase Shifters in Rectangular Waveguide," *IEEE Trans. on Microwave Theory and Tech.*, Vol. MTT-15, February 1967, pp. 87-95.