HIGH POWER L-BAND FAST PHASE SHIFTER*

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Abstract

A design of a waveguide-based, L-band, fast, high-power phase shifter is proposed. The shifter uses two magnetically biased blocks of Yttrium Iron Garnet (YIG) positioned in contact with the side walls of a rectangular waveguide. The cross-section of the waveguide is chosen to suppress unwanted RF modes that could otherwise compromise performance of the phase shifter. Static bias field in the YIG blocks is created by permanent magnets. Low inductance coils in the same magnetic circuit excite changing component of the bias field. Design of the device ensures effective heat extraction from the YIG blocks and penetration of the fast magnetic field inside the waveguide with minimum delay. This paper summarizes main steps in this development and gives brief description of the phase shifter.

INTRODUCTION

The attractiveness of using devices that control phase and amplitude of input RF power of superconducting accelerating cavities of a high-power linac is widely recognized [1]. Once implemented, this approach will result in significant savings in number of klystrons. This motivates multiple efforts towards building a high-power, fast phase and amplitude modulator, also known as vector modulator [2], [3]. At Fermilab, a prototype of a waveguide-based phase shifter was built and tested to demonstrate high power handling capability: up to 2 MW at 1300 MHz [4]. The phase shift range of this device was limited by the onset of sparking in the ferrite-loaded waveguide. Understanding the nature of the this effect was considered crucial for improvement of the performance, and a study was conducted that connected the sparking with the excitation of one of several resonant modes in the ferrite-loaded part of the waveguide [5]. The resonant modes could exist due to imperfections in positioning of the YIG blocks inside the waveguide or due to some difference in the levels of the bias field in the blocks. Variations in the magnetic properties of the YIG blocks can also result in resonances. Following this phase shifter performance study, a way to design a resonance-free system was proposed [6].

In the end, the answer to the question of whether the use of vector modulators in RF distribution system of a linac is advantageous in comparison with the "one transmitter per cavity" approach is in the complexity of a power system needed to activate the device. An impact of possible design solutions on requirements for the power supply must be closely watched.

This paper summarizes results of the phase shifter prototype performance study and presents a design concept of a fast, high-power phase shifter. The operating frequency (1.3 GHz) and the transmitted power requirement (~125 kW per one phase shifter) were chosen having in mind an elliptical (TESLA-type), nine-cell superconducting cavity.

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PHASE SHIFTER PERFORMANCE

Dynamic range of the phase shifter prototype described in [4] depended on the input power. It was ~90º at 100 kW and reduced to ~30º at 1500 kW due to onset of sparking in the gaps between the YIG blocks and the walls of the waveguide. The sparking could be stopped by partial filling the waveguide with SF_6. The sparking was the result of RF electric field increase when one of trapped RF modes in the ferrite-loaded waveguide was close to resonance and got coupled with the main TE_{10} mode.

In the regular section of the prototype's waveguide (165.1 mm x 50.8 mm), the modes TE_{11}, TM_{11}, TE_{20}, TE_{21}, etc. have critical frequencies higher than 1300 MHz. Only TE_{10} mode can propagate along the waveguide – the critical wavelength of this mode is 330.2 mm versus the free space wavelength at 1.3 GHz of 230.8 mm. In the ferrite-loaded section of the waveguide, critical frequencies for all modes shift to lower values; as a result, these modes can propagate in this section. Each high-order mode can be excited if there is a coupling with the main TE_{10} mode. If the coupling is small, corresponding mode can have a quality factor high enough for the electric field to exceed the breakdown threshold setting off the sparks.

The following subsections show which high order modes exist in the ferrite-loaded section and how they are coupled with the main mode.

TE_{20} Modes

If the two YIG blocks of the phase shifter are identical, positioned in the same longitudinal space, and have equal magnetic bias, TE_{20} mode is not coupled with the main mode: coupling with one of the blocks is cancelled by coupling with another one. By introducing bias asymmetry, or moving one of the blocks longitudinally, the coupling through electric and magnetic field is made possible. As a result, trapped resonance condition can exist for TE_{202} or TE_{203} mode. To ensure the absence of the coupling, the bias field in the blocks must be equal.

TE_{11} Modes

The presence of the YIG blocks makes it possible for the RF modes with variations along the short side of the waveguide to exist. In this case, the section of the waveguide between the YIG blocks is impassible for the modes. Each block supports its own oscillation mode, and these modes can be excited independently. It means that we will observe not a pure TE_{11} mode, but two separate quarter-wave TE_{11}-like modes. If there is symmetry in the vertical position of one of the blocks, no coupling with the main TE_{10} mode exists for corresponding modes. Shifting the block up or down relative to this symmetry position results in coupling.

TE_{10} Mode

If direction of the bias field is the same in the two YIG blocks, additional resonances could take place because of circular polarization of the magnetic field vector in the blocks. In case of circular polarization, the wavelength at given frequency depends on direction of wave propagation. For the TE_{10} mode, the polarization is opposite for the two sides of the waveguide, and significant phase difference can exist between the two sides of the ferrite-loaded section, which can result in resonant condition.

In [5] it was shown by modeling and proved by making direct RF measurements how resonances appear in a ferrite-loaded waveguide and what measures help to avoid them. Certain recommendations were made there on how to improve RF properties of the tested phase shifter. Based on these recommendations, a design has been proposed, which is described below.

PHASE SHIFTER DESIGN

Following recommendations of [5], the next changes in the prototype design have been made to improve the performance of the phase shifter. First, the width of the loaded waveguide was made smaller, which increased the cut-off frequency of the TE_{20} modes. Second, the height of this section was made smaller, which resulted in higher cut-off frequency of the TE_{11} modes and relaxed requirements for the fast bias power supply. Finally, the thickness of the YIG blocks was reduced, which allowed lower bias field and simplified heat management. Fig. 1 shows main features of the proposed design.

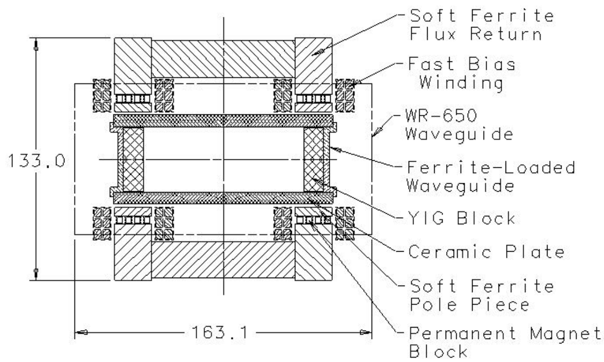

Figure 1: Design concept of a fast phase shifter.

Two YIG blocks, 11 mm wide and 35 mm high each, are placed inside a rectangular waveguide (110 mm wide and 36 mm high) in close contact with the side walls. Heat generated in the blocks is removed by cooling the walls. The magnetic system, built around the waveguide, is made to ensure needed bias field in the blocks. There are two components of the bias: static and dynamic. Static bias is created by using blocks of permanent magnets with the help of pole pieces and a flux return. The direction of this bias field is opposite in the two YIG blocks. To generate fast changing bias field, copper windings are used. Because the permanent magnets and the fast bias windings share the same magnetic circuit, spatial shape of the bias field in the absence of the waveguide is essentially the same for the static and dynamic magnetic field components. Eddy currents in the walls of the waveguide affect the dynamic component of the magnetic field; special design measures are needed to ensure the field penetration inside the waveguide. To handle both the static and dynamic components of the magnetic flux, the pole pieces and the flux return must be made of soft magneto-ceramic.

RF Design

RF design of the phase shifter provides a framework for configuring the rest of the device. The phase shifter must handle certain levels of peak and average power and provide required phase shift. The geometry of the ferrite-loaded section and range of the bias field change define performance of the device and configuration of the magnetic circuit. On the other hand, magnetic circuit imposes some limitations on the RF design, and several iterations in the design were made before reasonable convergence was achieved. The optimization goals were to get greater phase shift in combination with smaller bias field and its range and to lower power dissipation in the system. As it was mentioned earlier, uncertainties in the bias field symmetry and accuracy of the block placement in the waveguide can result in the appearance of unwanted resonances with corresponding increase in the power loss. The geometry of the ferrite-loaded waveguide and the level of the static bias in the YIG blocks were chosen after analyzing sensitivity of the system to these uncertainties. The bias field of ~700 G was found to be optimal.

Fig. 2 shows phase shift and power loss diagram for the final version of the RF design.

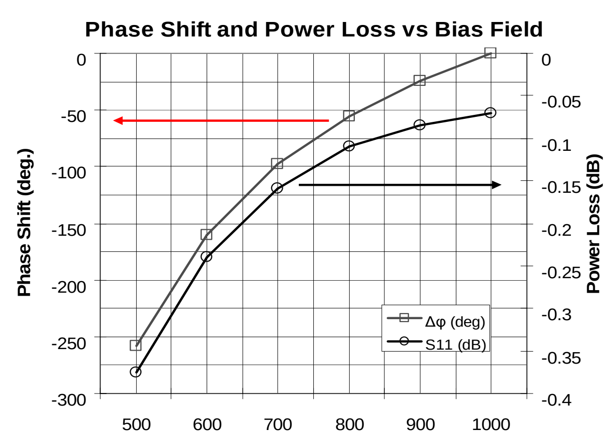

Figure 2: Power loss and phase shift diagram of the phase shifter. 110 mm x 36 mm ferrite-loaded waveguide.

The loss of power becomes more significant at lower bias, although it does not exceed 0.37 dB at 500 G. If the maximum allowed power loss is 0.3 dB, the magnetic bias change from 550 G up to 850 G (±150 G relative to the static bias value of 700 G) results in the phase shift of ~170º.

As a result of the RF stage of the design, the geometry of the ferrite-loaded waveguide, the static bias field level, and the fast bias field change range were chosen. Using this data as an input, magnetic circuit design was made, which is summarized in the next subsection of the paper.

Magnetic Design

The static bias field in the YIG blocks is created by permanent magnets; so, only the dynamic bias circuit, which uses copper windings to generate fast changing bias field, will require a power supply. To ensure penetration of the fast bias field in the YIG blocks, the walls of the ferrite-loaded waveguide are made by applying 5-µm copper coating on the surfaces of ceramic plates that form the top and the bottom of the waveguide in Fig. 1. Also, because the permanent magnet material of choice (SmCo-2:17) has electrical resistance similar to that of stainless steel, each permanent magnet block is made of several smaller blocks separated by gaps.

Six-turn fast bias windings are placed around each pole of the device and connected in series. The current in the winding of ±100 A is needed to create the required fast bias field swing of ±150 G. Parameters of the fast bias excitation circuit in Table 1 are shown for the frequencies 1 kHz and 20 kHz. The difference in the parameter values at different frequencies is due to skin effect.

Table 1: Fast Bias Current Circuit Parameter

f (Hz)	1000	20,000
R (mOhm)	50	900
L (µH)	56	36
ωL/R	6.77	5
U (V) @ 100 A	~40	~480

The inductance in the fast bias circuit limits the current change rate, which depends on the applied voltage. Based on the inductance data from Table 1, the phase shift rate per 1 V is ~0.02 º/µs. Besides, even with the 5-µm thin waveguide walls, penetration of the magnetic field inside the waveguide will be delayed relative to the current pulse. The field penetration analysis for realistic geometry shows that the time constant of the field diffusion is ~25 µs. Combined phase change delay relative to the voltage pulse is ~10 µs and almost does not depend on the level of the applied voltage. The maximum phase shift rate at 100 V is ~2 º/µs. A higher voltage must be used if a greater phase shift rate is needed.

Power Handling Capability

Two factors must be taken into account while trying to define the ultimate power the device can handle: the heating of the YIG blocks and electrical breakdown in the ferrite-loaded section of the waveguide. Requirements to the device naturally depend on the power requirements to the accelerating system; they also depend on details of the phase shift algorithm in the low level RF control system. If a superconducting, TESLA-type, nine-cell cavity is used with 25 MV/m accelerating gradient and 10 mA beam current, the required input RF power is ~250 kW. As it was pointed out in [3], accelerating structure must be separated from a vector modulator by a circulator. In this case, each phase shifter in the vector modulator sees only half of the power, or ~125 kW. For this power level and with 3.3% duty factor, the temperature rise in the hottest spot of the YIG blocks is ~10ºC [6].

In our previous work [4] the trapezoidal shape of the YIG blocks was used to avoid the sparking. Other solutions can also be used, e.g. encapsulating the blocks in polyethylene (the absence of gaps between the top of the block and the wall of the waveguide must be ensured), or increasing the air pressure in the waveguide, or filling the waveguide with SF_6. Without using any of these measures, in our case, with the input power of 125 kW, the electric field in the 0.5-mm air gap between the YIG block and the waveguide wall reaches ~22.5 kV/cm, which seems marginally OK.

CONCLUSION

Following the power test of a conceptual prototype of a waveguide-based phase shifter, a design study was undertaken that have resulted in a concept of high power, fast, L-band waveguide-based phase shifter. This concept can be used as a base for future attempts to configure an RF distribution system with the set of parameters different from what was used in this exercise. To complete this development, a prototype of a vector modulator must be built and tested.

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