FERMILAB-CONF-09-669-TD

Fast High-Power Microwave Ferroelectric Phase Shifters for Accelerator Application

S.Yu.Kazakov,[a,b] S.V.Shchelkunov,[c] V.P.Yakovlev,[a,d] A.Kanareykin,[e] E.Nenasheva,[f] J.L.Hirshfield,[a,c] Timergali Khabiboulline,[d] H. Hahn,[g] and E.M. Choi[g]

[a]*Omega-p,Inc., 199 Whitney Ave., New Haven, CT 06511, USA*
[b]*High Energy Accelerator Research Organization, KEK, Tsukuba, Ibaraki 305-0801, Japan*
[c]*Beam Physics Laboratory, Yale University, 272 Whitney Avenue, New Haven, CT 06511, USA*
[d]*Fermi National Accelerator Laboratory, Batavia, IL 60510, USA*
[e]*Euclid Concept LLC, Solon, Ohio 44139, USA*
[f]*Ceramics Ltd., St. Petersburg, 194223, Russia*
[g]*Brookhaven National Laboratory, Upton, NY 11973, USA*

Abstract. Measurements are reported for a one-third version of a high-power L-band ferroelectric phase shifter. This phase shifter is designed to allow rapid adjustments of cavity coupling in an accelerator where RF source fluctuations, microphonics, or other uncontrolled fluctuations could cause undesired emittance growth. Experimental measurements of phase shift *vs* externally-applied voltage, insertion loss, and switching speed are presented. An average switching rate of less than 0.5 ns for each degree of RF phase has been measured.

Keywords: microwave, phase shifter, ferroelectric.
PACS: 07.57.-c.

INTRODUCTION

During the operation of accelerators it is often important to rapidly change the phase and amplitude of the input RF wave that is fed to the acceleration structure. For this purpose a fast phase shifter has been designed for operation in L-band. The phase shifter is based on a new ferroelectric ceramic, whose permittivity changes with external application of an electric field [1]. The switching time depends on only the external HV circuit and can thus be less than one microsecond. In an earlier publication, results of measurements of properties of large ferroelectric rings were presented, and designs of coaxial and coaxial-planar phase shifters were suggested [2]. However, it emerged that these designs have a number of technical problems. The coaxial version is very complicated to manufacture, because it requires brazing of a large ceramic cylinder to the coaxial walls. The coaxial-planar version is simpler to manufacture, but the large volume of ferroelectric ceramic evidently leads to a high spectral density of parasitic modes that, in turn, leads to electric field enhancement and additional losses in the phase shifter. A new design of the phase shifter is now

CP1086, *Advanced Accelerator Concepts: 13th Workshop,* edited by C. B. Schroeder, W. Leemans, and E. Esarey
© 2009 American Institute of Physics 978-0-7354-0617-9/09/$25.00

suggested that has the advantages of the coaxial-planar design, but with a smaller volume of ceramics.

NEW PLANAR GEOMETRY

The new approach is to employ a single-mode ceramic waveguide. But, to reduce the RF fields in the device one uses a number of identical single-mode dielectric waveguides connected in parallel. In this situation the device has a sparse spectrum that can be controlled by changing its geometrical parameters. The dielectric constant of the ferroelectric ceramics to be employed is about ~500. For this dielectric constant the maximum transverse cross section of a single-mode waveguide is about 5 × 6 mm. A geometry was found that allows one to match an empty waveguide to a multi-rod dielectric waveguide, one layer of which is shown in Fig. 1. The matching linear ceramics having a dielectric constant of ~21 are placed before and after the ferroelectric waveguides.

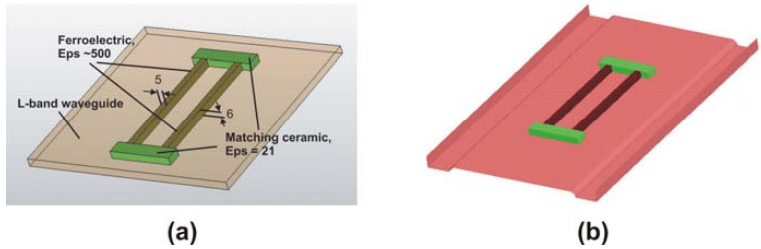

FIGURE 1. (a) New planar geometry. (b) Geometry for simulation

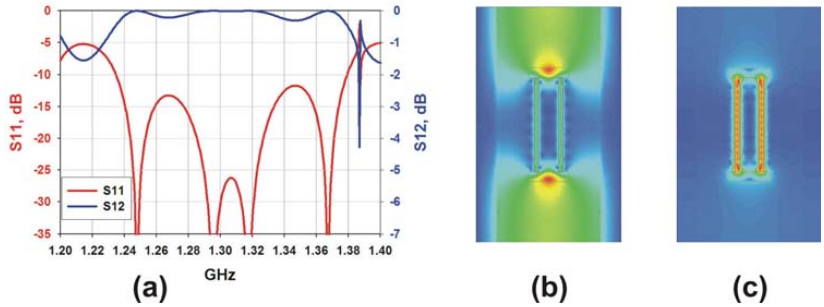

FIGURE 2. (a) Frequency response for new planar geometry. (b) Electric field. (c) Magnetic field.

In Fig. 2a the calculated scattering matrix parameters *vs* frequency are plotted. Fig. 2b and 2c show the field distributions for this kind of structure. One can see that the fields are concentrated in the ferroelectric slabs. In Fig. 3a the full geometry of the phase shifter is presented. The waveguide is divided into three stacked sections, and each section contains the assembly shown in Fig. 3b. There is a HV electrode between the assemblies, where the bias voltage is applied that changes the ferroelectric dielectric constant. In order to match all three parts to the WR650 waveguides, two

cylindrical ceramic rods with a dielectric constant of 9.8 are used. This matching scheme provides for equal power flow in all the three layers.

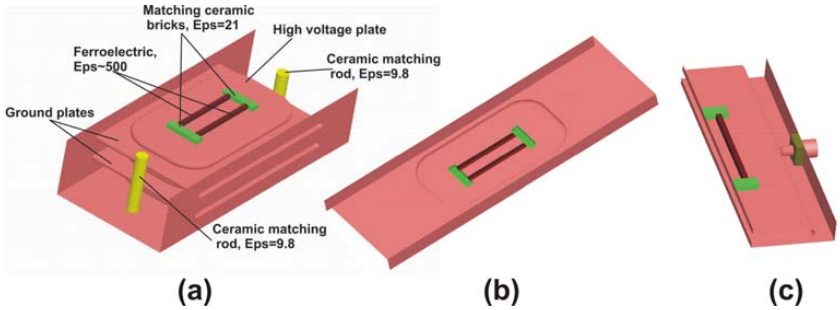

FIGURE 3. (a) Full geometry of phase shifter. (b) 1/3 part of phase shifter. (c) HV input

The HV input for the bias voltage is placed in the region where the RF fields are small, as seen in Fig. 3c. Calculated reflections are shown in Fig. 4a, while calculated losses *vs* ferroelectric loss tangent are shown in Fig. 4b. Table 1 shows the phase shifter parameters.

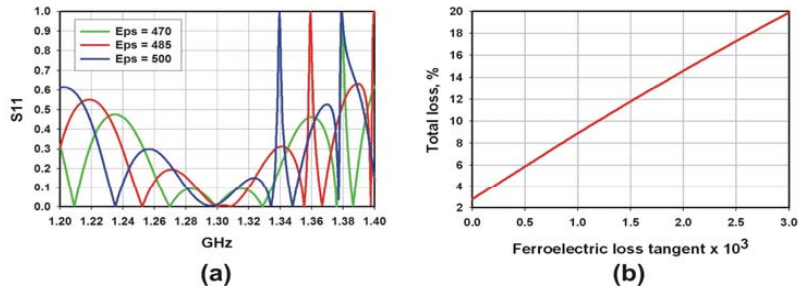

FIGURE 4.(a) Calculated S11 parameter of full geometry of phase shifter vs. frequency. (b) Calculated loss of full geometry vs. ferroelectric loss tangent.

TABLE 1. Phase Shifter Design Parameters

ferroelectric permittivity (at $V_{bias} = 0$), ε	~ 460
∂(phase)/$\partial\varepsilon$, degree	4
max. RF electric field (P = 500 kW), kV/cm	5.9
max. DC electric field, [Δ(phase)=120 deg], kV/cm	15
total loss for ferroelectric loss tangent tan(δ) , %	$2.8 + 6\cdot10^3 \tan(\delta)$

LOW POWER MEASUREMENTS OF 1/3 MODEL

Measurements of Phase shift

In order to check the design, a model was fabricated for one-third of the full design, namely a single layer. The model layout is shown in Fig. 5a, and a photo is shown in

Fig. 5b. The model may be disassembled in order to test a variety of ferroelectric bars. Tests were made with gold-plated ferroelectric bars and matching slabs, and contact to the copper walls was provided by liquid InGa alloy or by indium solder. Results of measurements of phase shift are presented in Fig. 6; these are seen to be in very good agreement with simulations.

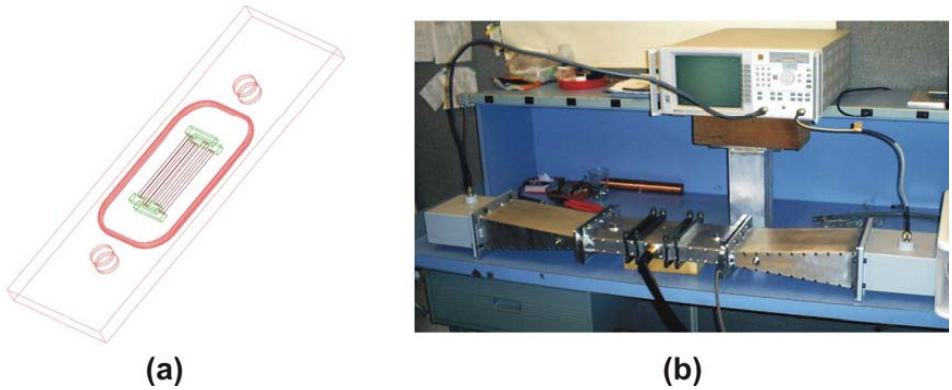

FIGURE 5. (a) Scheme of 1/3 model. (b) 1/3 model under test.

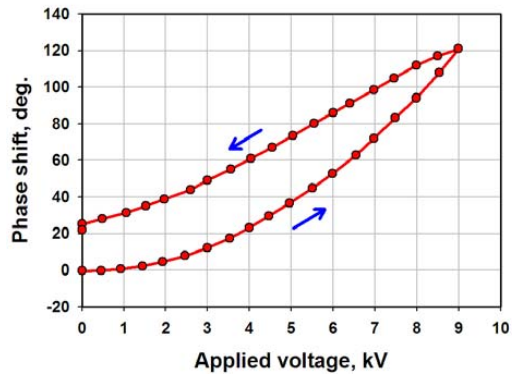

FIGURE 6. Measured phase shift of RF signal transmitted through 1/3 model *vs* applied bias voltage.

Measurements of Switching Speed

A vital property of any tuner is its response time, which for many accelerator applications should be less than 100 ns. This is clearly shorter than what can be achieved with a ferrite tuner, for example. Measurements of response time were made using the arrangement shown in Fig. 7. The high voltage rise/fall times from the available pulse generator were in the range of ~100 ns (measured as the time difference from 5% to 95% of the voltage maximum).

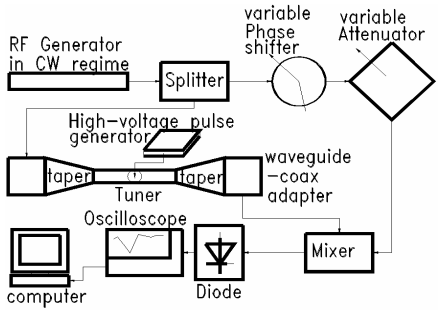

FIGURE 7. The signal from the RF generator at 1,290 MHz is split in two. One portion was directed through a phase shifter and attenuator directly to a mixer, while the second portion was fed through the tuner input port, passed through the tuner, picked up at the tuner output port, and then fed to the mixer. The resulting signal from the mixer was detected by a diode and monitored at an oscilloscope, and also captured by a computer for further signal processing (mainly FFT).

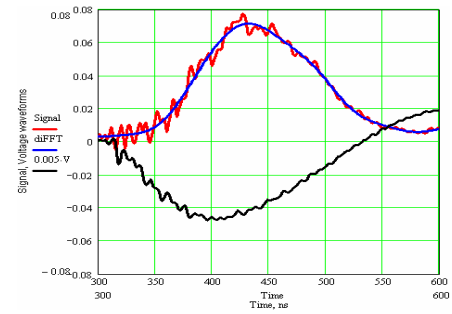

FIGURE 8. Time-response of phase shifter. Red curve (convex) is the difference between data with RF off and RF on. Blue curve (also convex) is the processed red curve after direct and inverse FFT with filtering out of high spectral components; the black curve (concave) is the high-voltage pulse. The vertical scale for the latter is reduced by a factor of 2×10^5; its peak value was 9.7 kV. It is seen that the time delay between the peak voltage and the peak variation in phase is 28 ns. (This value excludes delays in cables.) Note the time scale is 50 ns per division.

Switching speed measurements (each averaged over 16 shots) were processed by subtracting data with RF off from data taken with RF on, and are shown in Fig. 8. The difference signal of 67 mV from the mixer corresponds to a phase change of 77º. From these data, where the response time of the phase shifter is dominated by the 90 ns rise time of the voltage pulse, one can infer that the response time to a step function voltage would be equal to or less than the delay time, namely approximately 30 ns. This could be interpreted to correspond to an average switching rate of less than 0.5 ns for each degree of RF phase

Measurements of Loss

The loss tangent of ferroelectric bars was measured for the uncoated bars (manufactured from the same batch used to make the bars coated with gold). The value of loss tangent was determined to be ~2×10^{-3}, suggesting that the 1/3 scaled tuner model may suffer a transmission loss no better than ~0.7dB.

In actuality, the measured transmission lower, with lowest transmission loss only when we used either freshly applied liquid InGa or soldered the bars to the waveguide walls (using In). However, we were never been able to apply more than 4 kV to the soldered configurations; hence we discuss below only the structures assembled with liquid InGa. It was found that in the configurations with fixed structure height, when the top and bottom walls are tethered by bolting to the side walls, the transmission dropped when the voltage grew [see e.g. Fig. 9]. However, in a configuration where the top wall was resting without tethering on the ceramic bars under 200-400 lbs load, the transmission did not drop so much. However, in general,

the transmission level was lower because of leakage radiation through the gaps formed between unbolted walls, or in some cases became even higher [see e.g. Fig. 10]. This suggests the presence of piezoelectric effects that lead to the contraction of the bars and degradation in quality of the bar-wall surfaces contacts.

It is anticipated that successful brazing of the ferroelectric and matching dielectric bars will eliminate losses beyond those in the bulk ceramics and metallic walls, as well as to lead to transmission being independent of applied voltage.

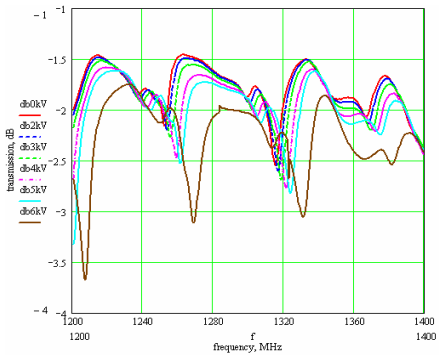

FIGURE 9. The transmission drops when the voltage grows in the configurations with fixed structure height (the top and bottom walls are tethered by the side walls), suggesting a piezoelectric contraction of the bars.

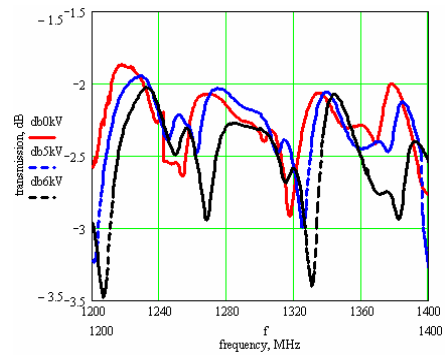

FIGURE 10. In the configurations where the top wall was resting (under 200 - 400 lbs load) on the ceramic bars, and was not bolted to the side walls the transmission did not drop so much, or in some cases even get higher

CONCLUSION

Measurements for a 1/3 version of an L-band tuner give phase shifts in good agreement with theory, rapid (~30 ns) switching speed, but excessive insertion loss. It is our understanding that the losses are partially caused by the bad contact between ceramic and the waveguide walls, and is not an intrinsic property of the phase shifter. Lastly, the tuner was connected to a 1.3 GHz cavity and confirmed the capability of fast tuning of its resonance frequency.

ACKNOWLEDGMENT

This work was supported by the Office of High Energy Physics, US Department of Energy.

REFERENCES

1. S.Yu. Kazakov, V.P. Yakovlev, S.V. Shchelkunov, A.D. Kanareikin, E.A. Nenasheva, and J.L. Hirshfield, “First Measurements of RF Properties of Large Ferroelectric Rings for RF Switches and Phase Shifters,” PAC2007, Albuquerque, June 25-29, 2007.
2. V.P. Yakovlev, S.Yu. Kazakov, and J.L. Hirshfield, “1.3 GHz Electrically-Controlled Fast Ferroelectric Tuner,” EPAC2006, Edinburgh, June 26-30, 2006, pp. 487-489