FIRST MEASUREMENTS OF RF PROPERTIES OF LARGE FERROELECTRIC RINGS FOR RF SWITCHES AND PHASE SHIFTERS *

S.Yu. Kazakov[1,2], V.P. Yakovlev[1,3], S.V. Shchelkunov[4], A.D. Kanareikin[5], E.A. Nenasheva[6] and J.L. Hirshfield[1,3]

[1]Omega-P, Inc., New Haven, CT 06511, USA
[2] High Energy Accelerator Research Organization (KEK), Tsukuba, Japan
[3]Physics Department, Yale University, New Haven, CT 06520, USA
[4]Department of Applied Physics, Columbia University, New York City, NY 10027, USA
[5]Euclid TechLabs, LLC, Solon, OH, USA
[6]Ceramics, Ltd, St. Petersburg, Russia.

Abstract

Fast, electrically-controlled ferroelectric RF switches and phase shifters are under development by Omega-P, Inc. for different accelerator applications in the X-, Ka- and L-bands. The exact design of such a devise depends on the electrical parameters of particular ferroelectric material to be used, namely its dielectric constant, loss tangent and tunability. The exact values of these parameters were unknown in these frequency domains for large rings of low loss ferroelectric material that is planned to be used. New methods were developed in order to measure parameters of large rings in order to determine if the behavior of large bulk samples is the same as the behavior of small samples, and to be sure that manufacturing technique preserves desired properties for large rings. The results of measurements are presented.

INTRODUCTION

A ferroelectric ceramic has an electric-field-dependent dielectric permittivity that can be rapidly altered by application of a bias voltage pulse. Typical ferroelectric ceramics are so-called BST ceramics based on solid solutions of $(Ba,Sr)TiO_3$. Ferroelectrics have unique intrinsic properties that make them extremely attractive for high-energy accelerator applications. The response time is limited by the external electronic circuit that generates and transmits the high-voltage pulse, and can thus be in the ns range [1]. Unlike semiconductors and plasma devices, ferroelectrics allow their dielectric properties to be switched up and down (i.e., altering the dielectric permittivity and then restoring the initial value), using a single external control pulse, thus offering unique capabilities for high-power tuning and switching device design. High dielectric breakdown strength, low gas permeability, and relatively simple mechanical processing make ferroelectric ceramics promising candidates to be the active material in accelerator tuning and switching devices in X, Ka and L-bands [2,3].

Euclid TechLabs recently developed and tested a modified bulk ferroelectric based on a composition of BST ceramics with magnesium-based additives that has a relative permittivity ε = 550-600, and a 20% change in permittivity for a bias electric field of 50 kV/cm [1]. A technology was developed for fabrication of large rings having diameter of about 100 mm (see Fig. 1) for high power tuning and switching devices for accelerator applications [1]. However, the measurements of the dielectric constant, loss tangent and tunability were initially performed for small samples only, i.e., for so-called “witness” samples that are made of the same material as large rings and have the same processing procedure. The measurements for the material prototype BSM-3 [1] yielded a dielectric constant of 580-590, a loss tangent of 0.002 at 3 GHz, and a permittivity decrease by 20-22% at 40-50 kV/cm of a bias field for the case of parallel bias (i.e, the case when the bias field is parallel to the RF electric field), and by 13-16% at 40-50 kV/cm for perpendicular bias (i.e., the case when the bias field is perpendicular to the RF electric field). Note that for the considered ferroelectric ceramics the loss factor is proportional to the frequency over a wide frequency range from 100’s of MHz to 10’s of GHz. New methods reported here were developed in order to measure parameters of large rings in order to determine if the behavior of large bulk samples is the same as the behavior of small samples, and to be sure that manufacturing preserves good properties for large rings. The tests of the large rings include (i) dielectric constant measurements, (ii) loss tangent measurements and (iii) tunability measurements.

Figure 1: The large ferroelectric ring having the inner diameter of 104.2 mm, thickness of 2.6 mm, and length of 20.4 mm

GENERAL

In order to measure parameters of a large ferroelectric ring, a special two disc test cavity was designed. The

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cavity concept is shown in Figure 2. The ferroelectric ring is placed between two discs, the HV DC bias may be applied the upper disc for tunability measurements. The cavity has removable rotating probes for mode identification, and a circular groove with two other probes for tunability measurements at high voltage. The photo of the test cavity is shown in Figure 3.

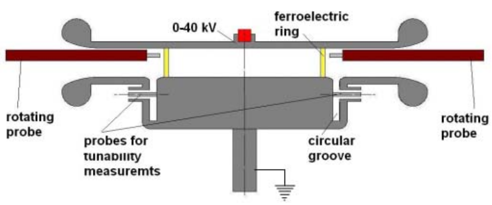
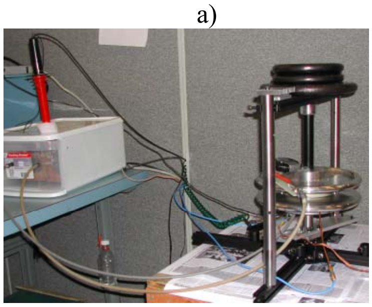


Figure 2: Schematic of the test cavity for the large ferroelectric ring measurements.

a)



b)

Figure 3: Experimental setups for (a) dielectric constant and (b) tunability measurements.

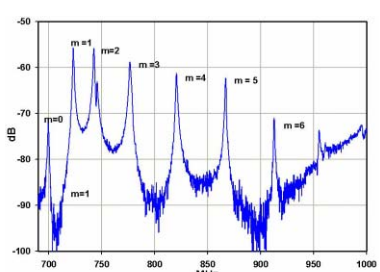


Figure 4: Example of the measured spectrum.

The cavity spectrum was measured and calculated. An example of a measured spectrum is shown in Figure 4. Comparison of the calculated spectrum and the measured spectrum gave the value of dielectric constant $\varepsilon = 580$ that is the same as that measured for small samples.

The loss tangent at frequencies below 1 GHz is small, less than 0.001, so it is necessary to include or take into account other sources of RF losses in order to avoid overestimation. For loss tangent measurements the aluminum cold model cavity of the X-band switch [2] was used, because for the two disc cavity it is a problem to exclude radiation loss from the gap between the discs. The cold model cavity is shown in Figure 5. In order to avoid losses caused by imperfect contact between the ring metallization and the discs, the TE_{011} mode was measured as it has no radial currents. The measured quality factor for this mode is 880 and resonance frequency is 769 MHz. The Ohmic losses in the aluminum walls of the cavity were measured for TE_{011} mode in the cavity without the ferroelectric ring in order to avoid the influence of the contacts between the cavity caps. The quality factor was measured to be 3250 at the resonance frequency of 7493 MHz. It gives a value of loss tangent for the ferroelectric of about 5×10^{-4} that is the same as for small samples at the same frequency.

Figure 5: The cold model of the X-band switch cavity used for loss tangent measurements. The ferroelectric ring was placed into a circular sitting place shown in the photo.

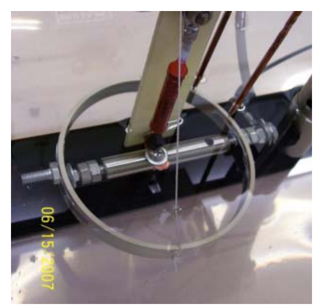


Figure 6: Experimental setup for the ring tunability measurements at high voltage. One can see the ring, RF probes and fixtures.

For the tunability measurements at bias voltages below 20 kV/cm the two disc cavity was used; see Figure 3b. The bias field is applied to the ring in the axial direction. This setup allows measurements with both parallel bias (for TM modes) and perpendicular bias (for TE modes). However, breakdown in air does not allow measurements at higher field (the X-band switch will operate at 50 kV/cm). For higher bias voltage the setup shown in Figure 6 was used. Internal and external surfaces of the ring are covered by conductive Ag ink, and the bias field is applied in the radial direction. The assembly that includes the ring, fixtures for HV electrodes and RF probes is placed in oil. This setup allows measurements of the parallel bias only, because RF modes in this frequency range have a TEM-like structure and only radial component of electric field. The results of the parallel tunability measurements are shown in Figure 7. The maximum change in dielectric constant is about 22% at 50 kV/cm, which coincides with the measurements for small samples. Note that the material response for parallel bias in the axial direction (red dots) coincides with the response for the bias in radial direction (green dots). The results of the perpendicular tunability measurements are shown in Figure 8. A simple linear extrapolation shows that the perpendicular tunability is not worse than ~11%.

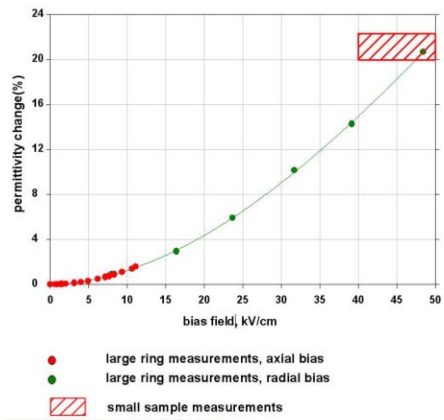


Figure 7: Parallel tunability for BSM-3 material prototype.

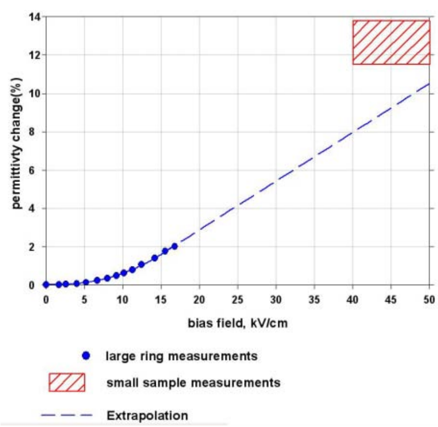


Figure 8: Perpendicular tunability for BSM-3 material prototype.

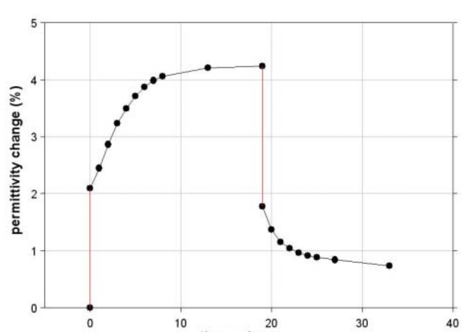


Figure 9: Long-term drift of the dielectric constant and hysteresis for BSM-3.

Long-term drift of the dielectric constant was observed, as follows. A bias of ~13 kV/cm was turned on at $t = 0$ that changed the permittivity by 2.0%. During a 19 minute interval, this bias was maintained, but the permittivity increased by 2.3%. At $t = 19$ minutes the bias was turned off, and the permittivity changed instantaneously by 2.0% and than relaxed to the value that differs from the initial value by 0.7%.

It should be noted that the large rings are to be used in X-, Ka- and L-band devices in a pulsed regime, so that a pulse bias voltage will also be used. The small sample behavior subject to pulsed bias was observed, and the material time response was found to be smaller than 10 nsec [1]. However, with DC bias for the material prototype BSM-3, long-term drift and hysteresis were found as shown in Figure 9. These effects should not influence ring operation in the short pulse regime (e.g., X-band switch and phase shifter, Ka-band switch, L-band phase shifter for ILC). These effects would not rule out CW operation, for example for phase shifters for ERLs [4], where these effects could be compensated using a feedback system with bipolar HV bias source. Further investigations of this peculiar phenomenon are underway.

In Figures 10 the results of measured parallel tunability of a new advanced material, BSM-4 [1] are presented. One can see that the permittivity change reaches 36% at a bias field of 45 kV/cm. Other parameters (dielectric constant, loss factor) are currently being measured.

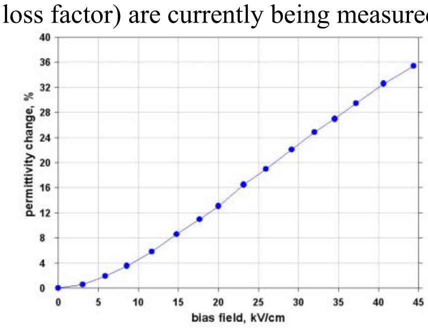


Figure 10: Parallel tunability for BSM-4 ferroelectric material. The ring inner diameter is 29 mm, thickness is 2 mm, and length is 7 mm.

CONCLUSIONS

Parameters of large ferroelectric rings made of the ferroelectric material prototype BSM-3 were measured for the first time and were compared with measurements for small samples. Dielectric constant, loss factor and tunability for the large rings are the same as for the small samples [1,5].

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