NEW DEVELOPMENTS ON LOW-LOSS FERROELECTRICS FOR ACCELERATOR APPLICATIONS

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Abstract

Recent results on development of BST (barium strontium titanium oxide composition) ferroelectric materials are presented to be used as the basis for new advanced technology components suitable for high-gradient accelerators. The ferroelectric ceramic has an electric field-dependent dielectric permittivity that can be altered by applying a bias voltage. Ferroelectric materials offer significant benefits for linear collider applications, in particular, for switching and control elements where a very short response time of 10 ns can be potentially achieved. The BSM ceramic exhibits a high tunability factor: a bias voltage of 50 kV/cm reduces the permittivity from 500 to 400. The applications include: fast active X-band and Ka-band high-power ferroelectric switches, high-power X-band, and L-band ferroelectric-based phase-shifters. The recently developed large diameter (11 cm) BST-based ferroelectric rings will be used at high pulse power (tens of megawatts) for the X-band components as well as at high average power (in the range of a few kilowatts) for the L-band phase-shifters which are suitable for ILC applications.

INTRODUCTION

A ferroelectric ceramic is a material with an electric-field-dependent dielectric permittivity that can be very rapidly altered by an applied bias voltage pulse. Typical representative ferroelectric materials are $(Ba,Sr)TiO_3$ or a $BaTiO_3$ - $SrTiO_3$ solid solution (BST). The BST material can be synthesized in polycrystalline, ceramic layer and bulk forms. Ferroelectrics have unique intrinsic properties that make them extremely attractive for high-energy accelerator applications. The response time is $\sim 10^{-11}$ sec for the crystalline and $\sim 10^{-10}$ sec for ceramic compounds. Unlike semiconductors and plasma devices, ferroelectrics allow control of their dielectric properties in two directions using a single external control pulse, offering unique capabilities for high-power switching device design. High dielectric breakdown strength, low gas permeability and simplicity of mechanical treatment make ferroelectric ceramics promising candidates for the loading material in accelerator tuning and switching devices.

In order to develop rf technology for a future CLIC-like multi-TeV electron-positron linear collider in the millimeter wave frequency band, it is necessary to test the proposed high power rf components in realistic regimes to be able to determine the rf breakdown and metal fatigue limits. The typical required power for such tests in the Ka-band falls in the range of 200-300 MW with a pulse of 70-150 nsec [1]. This goal can be achieved by using of a long pulse rf source and by employing an rf pulse compressor. For example, if one has an rf power source of 30-50 MW with a pulse width of 0.5-1.0 μs along with an active pulse compressor with a compression ratio of 10:1, it would be possible to achieve the required power level of 200-300 MW for the ~100 ns pulses. The key element of the active pulse compressor is the fast, electrically-controlled high power ferroelectric microwave switch proposed in reference [1].

Note that it is possible to use an ultra-fast, electrically controlled phase shifter based on ferroelectric elements in the 1.3 GHz rf system of the superconducting version of a linear collider [2]. This phase shifter will offer the capability of changing the coupling of the rf cavity to the feed line by varying the bias voltage of the ferroelectric element in order to optimize the coupling for different regimes of collider operation (different beam loading, etc). In principle, these elements are fast enough to change the coupling during the rf pulse in order to a) decrease the time of the cavity discharge after the rf pulse ends and thus decrease refrigeration costs and b) minimize reflection during the rf cavity filling and reduce the total required rf power by ~10%. Note that ferroelectric devices are the only components that can provide fast double-switching during the rf pulse. In addition, the rf losses in a ferroelectric at 1.3 GHz are substantially smaller than at 11 GHz [2].

Development of a *tunable* Dielectric Loaded Accelerator (DLA) will allow one to adjust the phase velocity of the DLA after it has been assembled into its final form [3]. The need for frequency tuning (or phase velocity adjustment) of any accelerating structure arises from the fact that the phase velocity of the assembled accelerating structure will, in general, differ from the design phase velocity due to various sources of error. In a DLA structure, these errors can be caused by machining tolerance of the dielectric dimensions, thermal expansion of the structure, dielectric constant heterogeneity, etc. The method used to vary the frequency of a DLA structure consists of a thin layer of a ferroelectric material backing a layer of conventional ceramic. A DC bias voltage is used to vary the permittivity of the ferroelectric layer and thus tune the overall frequency of the DLA structure [3].

The newly developed ferroelectric technology has been experimentally validated at the Argonne Wakefield Accelerator in a tunable DLA structure experiment [3] and is under development at Omega-P Inc./Yale University for the demonstration of high power microwave switches and fast ferroelectric phase-shifters at both L-band for ILC and at Ka-band for high accelerating gradient research [1-2].

FERROELECTRIC COMPONENT DEVELOPMENT

The main requirement for the electrical properties of ceramic materials to be used in accelerator devices is a combination of relatively low dielectric constant in the range from 300 to 600 at an electric field tunability not less than 10 - 20% for a change in electric field magnitude in the 20-50 kV/cm (2-5 V/μm) range, and low dielectric losses in the microwave range ($tan\ \delta \le 0.005$ at 10 GHz) [4-5].

The required range of dielectric constants in $(Ba,Sr)TiO_3$ solid solutions with perovskite structure can be achieved by increasing the content of strontium titanate, in turn causing a shift of the Curie temperature. Barium strontium titanate solid solutions $(Ba_xSr_{1-x})TiO_3$ (x = 0.45 – 0.55) were synthesized by ceramic processing from titanium dioxide (TiO_2) and strontium and barium carbonates ($SrCO_3$, $BaCO_3$) or prefabricated barium and or strontium titanates ($BaTiO_3$, $SrTiO_3$). The initial materials were treated mechanically by mixing them in a vibration mill for three hours to particle size 1 μm before sintering.

Ferroelectric Microstructure Studies

We have completed successfully our preliminary research on BSM ferroelectrics over a range of compositions of $(Ba_xSr_{1-x})TiO_3$+MgO with various additives [4-5]. The ferroelectric was synthesized with the optimum ratio of barium and strontium components of the solid solution (x = 0.45-0.55) with magnesium compounds taken as additives. The new BST- MgO (BSM) ferroelectric material has been studied and optimized for use in tunable dielectric based accelerating components. The projected loss factor of the newly developed material is $(4\text{-}6)\times10^{-3}$ in the 10 GHz frequency range, the dielectric constant is in the range of 450-500, and the tunability is 20-30% at a 40-50 kV/cm dc bias field. Disk samples (1 MHz) of the BSM ferroelectric, and $22.8\times25.0\times(0.5\text{-}1.0)\ mm^3$ (X-band) and $3.4\times10\times(0.5\text{-}1.0)\ mm^3$ (Ka-band) planar samples have been fabricated for the dielectric response measurements described in [5]. X-ray phase analysis and electron microscopy imaging studies showed that the BST solid solution with MgO additives is presented in a heterogeneous mixture. The composite material includes two main crystalline phases: a solid solution with perovskite structure (BST) and magnesia (MgO) that is partly incorporated into the solid solution composition thus increasing its unit cell parameter. Some additional phases have been found in the phase composition of the samples. These are magnesium and barium polytitanates whose total amount depends on the composition, the raw materials, and the technology of sample preparation. This amount can exceed 5% and may significantly influence the level of dielectric losses of the ceramic ferroelectrics.

It should be noted that the initial raw materials and the sintering technology developed provide a high level of reproducibility of the phase structure of the tested samples, the unit cell parameter of the main BST phase as well as the composite microstructure. This is a promising precondition for achieving stable and repeatable dielectric response parameters at microwave frequencies.

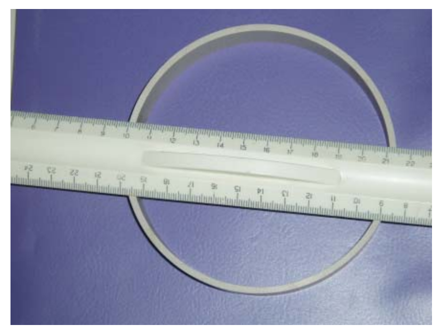

Figure 1: Large-diameter ceramic ring sample made of BST-MgO (BSM) ferroelectric. The ring diameter is of 110 mm and the ring thickness is of 2.8 mm.

Active Ferroelectric-Based Accelerator Component Fabrication

Active high power ferroelectric switches and phase-shifters require large diameter ferroelectric rings with electrical properties as presented in the previous section.

Initial samples of ceramic materials of BSM-type studied in this work are ceramic powders with particle size ~ 1 μm based on solid solutions of barium/strontium titanates with magnesia additives. The composition of these powders as well as their processing technology provides the capability of using various methods of forming ceramic half-finished products, widely used in ceramic technology. These are, first, methods of hydraulic and isostatic pressing used, in particular, for ceramic preforms as cylinders (pipes) of various lengths and cross-sections. We produced these shapes from ceramic powders analogous in composition and processing to those to be used as dielectric waveguides in accelerating systems**.** These combine high precision geometrical parameters and high stability of dielectric characteristics (ε and Q) in the microwave range. Meanwhile, the production of tubes and rings with cross-section diameters larger than 50 mm and relatively thin walls (≤ 5 mm) is a complicated technical problem. The solution requires using a complex of processing techniques, development of special accessories to provide for consolidation homogeneity of the press-forms for the selected structures, and selection of optimum sintering methods and final mechanical treatment of the ferroelectric surfaces. These technologies should provide the repeatability and homogeneity of the electrical properties of the ferroelectric during the course of processing.

This kind of technology provides uniform hydraulic pressing at the horizontal plane of the ring. At the same time, for a ferroelectric tube with diameter ~ 100-120 mm made of small grain powders we used modern methods of forming these tubes, particularly the *combination* of hydraulic and *isostatic* pressing. This combined technology ensures the homogeneous compression of the material along the total ring length to provide uniform dielectric properties along the waveguide length. This results in a significant decrease in the probability of the appearance of macro-defects in the bulk of the ring (tube) during sintering and increases the uniformity of the ferroelectric parameters

Fig. 1 shows one such large diameter ferroelectric ring (100-120 mm). Rings of 108 mm diameter, 20 mm length and 2.8 mm thickness have been fabricated for the active ferroelectric switch development program with Omega-P Inc./Yale University.

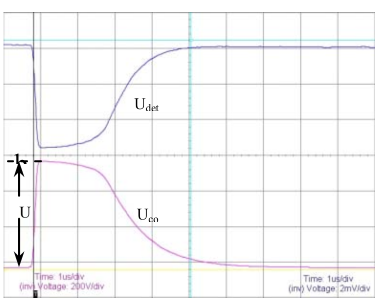

Figure 2: Typical time profiles of the control (biasing) pulse voltage and the BSM ferroelectric response after detection.

Time Response Measurements

Active high power ferroelectric switches and phase-shifters require large diameter ferroelectric rings with dielectric properties as specified previously. A test fixture for the short pulse (rise time of 10 ns) ferroelectric time response measurements has been developed [6]. The test fixture can produce dynamic mode, bipolar and uni-polar high voltage pulses with amplitudes up to 3 kV, and a rise time from 1 ns to DC.

The measurement procedure is illustrated in Fig. 2, where the detector signal (a) and the control (biasing) signal (b) recorded on the oscilloscope screen are presented. Note the test fixture provides no distortion in time scale down to 1ns for control (biasing) pulses applied from the pulser to the capacitor loaded with the BSM ferroelectric. The shape of control (biasing) pulses presented in Fig.2 (rise time ~4ns, fall time ~1μs) was defined only by the parameters of the pulser that was used for this experiment. Note that with this experiment a short response time of a few tens of ns has been demonstrated for the bulk BSM ferroelectric at a high tunability exceeding 30% at 4 V/μm bias field in pulse mode [6].

SUMMARY

The primary objective of the research presented here is to establish the feasibility of the nonlinear ferroelectric material with properties required for accelerator applications. We have designed new BST materials intended for Advanced Accelerator Concepts applications, involving the entire production chain: synthesis of ceramic ferroelectric samples, study of their microstructure, shape and size distributions, dielectric response measurements in the 10-35 GHz frequency range, temperature dependence of the ferroelectric parameters like the Curie temperature, permittivity, loss tangent and tunability. We have developed large diameter (110 mm) ring samples to be used as switching elements for accelerator applications. We have demonstrated switching times on the order of tens of ns for the BSM ferroelectric substrates. All these efforts will result in demonstration of new ferroelectric materials with loss tangents in the range of $(3\text{-}4)\times10^{-3}$ at 10 GHz and tunability in the range of 25-35 % at 40 - 50 kV/cm biasing field.

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