LOW-LOSS FERROELECTRIC FOR ACCELERATOR APPLICATIONS

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Abstract

We discuss a newly developed nonlinear ferroelectric material especially for accelerator applications. This is a BST (Barium-Strontium Titanium oxides) and MgO composite material, or BSM. The ferroelectric ceramic has an electric field-dependent dielectric permittivity that can be altered by applying a bias voltage. BSM has unique intrinsic properties for high-energy accelerator applications: response time of $\sim 10^{-10}$-10^{-11} sec, considerably high rf breakdown limit of more than 150 kV/cm, and good vacuum properties. Bulk BSM ferroelectrics can be used as active elements of electrically controlled switches and phase shifters in pulse compressors or power distribution circuits of future linear colliders as well as tuning layers for the dielectric based accelerating structures. The new BSM ferroelectric shows a loss tangent of $4\text{-}6\times10^{-3}$ at X-band and Ka-band, and some samples have even showed better results. The BSM ceramic exhibits a high tunability factor: a bias voltage of 50 kV/cm reduces the permittivity from 500 to 400. The chemical composition, features of the technology process, and mechanical and electrical properties of the material are discussed.

INTRODUCTION

A ferroelectric crystal or ceramic is a material with a spontaneous dielectric polarization below some Curie temperature T_c. (Most of the properties of ferroelectrics are analogous to those of ferromagnetic materials except involving electrical rather than magnetic properties.) Typical representative ferroelectric materials are $(Ba,Sr)TiO_3$ or a $BaTiO_3$ - $SrTiO_3$ solid solution (BST). The BST solid solution 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 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 easy mechanical treatment make ferroelectric ceramics promising candidates for the loading material in accelerator tuning and switching devices.

Frequency control of any accelerating structure is a fundamental issue. Synchronization between the electron beam velocity and the phase velocity of the accelerating field must be maintained in order for the bunch to gain energy. Lack of frequency control causes problems for multistage accelerators where one has to match the accelerating field frequency and phase between adjoining sections. A method to vary the resonant frequency of a *dielectric loaded accelerating* (**DLA)** structure by an *electrically-controlled thin layer of ferroelectric* has been proposed and demonstrated [1].

The current design for the NLC relies on pulse compression to achieve the high peak rf power levels required to drive the accelerator structures (~500 MW in 400 ns pulses). The mechanisms by which these compressors operate are *passive*, in that no element in the pulse compressor structure has time-dependent properties. Common limitations of these systems are their relatively low compression ratio (~4:1), low efficiency and the need for very long runs (100's of km) of low-loss vacuum waveguide. In the *active* pulse compressor the coupling irises are replaced with fast high-power rf switches, which change the delay line coupling during the rf pulse. A *resonance switch* based on use of *electrically–controlled ferroelectric elements* has been proposed for use in active pulse compressors [2].

It would be possible to reduce substantially the length of waveguide required if a so-called "active DLDS" system could be developed. The key element of active DLDS is a high power microwave switch. There exist several ideas for such a switch, but the active element is invariably *a high power fast phase shifter*. In the case of the NLC, this phase shifter must change the phase of a 600 MW pulse by 180° within a few tens of ns.

Note that ultra-fast, electrically controlled switches based on ferroelectric elements may be used in the 1.3 GHz rf system of the superconducting linear collider. These elements may be incorporated into rf couplers. The coupler feeding the rf structure already has a built in DC bias in order to suppress multipacting. This bias may be used for tuning a ferroelectric element with the possibility of changing the coupling of the rf cavity to the feed line.

The newly developed ferroelectric technology will be experimentally applied at the Argonne Wakefield Accelerator for a tunable DLA structure experiment [1] and at Omega-P Inc./Yale University for the development and demonstration of a high power microwave switch and fast ferroelectric phase-shifter [2] in 2005-2006.

BSM FERROELECTRIC DEVELOPMENT

We have fabricated and experimentally tested BST ferroelectric samples which, when a dc bias field is applied allow varying of the effective dielectric constant of the rf resonator/waveguide loading and, therefore, tuning and control of the operating frequency of the device [3-4]. We have developed BST-MgO ferroelectric samples to be able to test the dielectric response in the 3-35 GHz frequency range as well as to define the tunability factor. We have studied the phase composition depending on the initial raw material and additives introduced. Microstructure of the samples and, in particularly, the shape and size of the crystals indicated a method of improving the dielectric parameters of the final BST-MgO composition. Sintering technology affecting the loss factor was a subject of study as well. We have developed and sintered large (up to 11 cm) ferroelectric rings and long tubes with thin walls for the key ferroelectric switching and control elements. We have studied the dielectric response of our BST-MgO samples with short (10s of ns) leading and tailing edge dc pulses.

Ferroelectric Sample Fabrication

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 the electric field tunability not less than 10 - 20% (electric field magnitude ~ 20-50 kV/cm (or 2-5 V/µm) and low dielectric losses in the microwave range (*tan* $\delta \leq 0.005$ at 10 GHz) [1,2,4].

The required range of dielectric constants in (Ba,Sr)TiO3 solid solutions with perovskite structure can be achieved by increasing the content of strontium titanate which is accompanied by 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.

Samples of required geometrical shape and size were prepared by hydraulic pressing. A 10% solution of polyvinyl alcohol was taken as a binder. The dependence of the dielectric properties on applied voltage was measured using disk samples (h = 0.5 mm) with evaporated copper electrodes. The thickness of the Cu-electrodes was about 3-5 µm. We used discs of 6 mm diameter and 0.5-1.3 mm thickness as well as 20×30×1 mm^3 plates at 3.5 - 11 GHz. Measurements at 8-11 GHz were done using 22×20×1.0 mm^3 substrate samples, and at 20-35 GHz we used 3.3×10×0.5 mm^3 plate samples polished on both sides.

Phase Composition and Microstructure

We have studied BST-MgO compositions with additives of rare earth oxides and compounds. These compositions provide a combination of high tunability of ε and low dielectric losses. The study of phase relations and structural characteristics of the phase mixture in connection with dielectric properties and tunability of BST-MgO system is crucial for bulk BST accelerator applications.

Bulk BST-MgO (BSM) ferroelectric samples have been fabricated. We used presynthesized barium and strontium titanates ($BaTiO_3$ and $SrTiO_3$) with grain sizes in the range of 1 µm and 0.3-0.7 µm. We manufactured disk ferroelectric samples for dielectric response measurements in the 1 MHz frequency range.

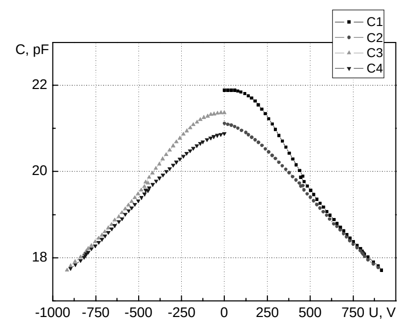

Figure 1. Capacitance vs. dc bias voltage for BSM ferroelectric samples, thickness of 200 µm, 4.5 V/µm applied field. Tunability is of 1.22.

BSM ferroelectric planar substrates of dimensions 22.8×25.0×(0.5-1.0) mm^3 and 3.4×10×(0.5-1.0) mm^3 have been developed for X-band and Ka-band tunable reflective resonator designs. The successful demonstration of this technology presented in [Kanareykin et al, these Proceedings] enables the development of new capabilities for tunable ferroelectric based accelerator components.

Dielectric response measurements

Regularities in the variation of dielectric properties (T_c, dielectric constant, tunability by dc bias voltage, and dielectric losses at rf and from 3.5 to 11.5 GHz) of the BSM samples have been studied as a function of the solid solution composition, Mg-containing additives, and the quality of raw materials. The proportions of the components were determined by the required range of ϵ=400-600, electric field tunability 1.22-1.29 at E~4.5 V/µm (Fig.1), and Q-factor 110 - 290 at f~11GHz. The compounding and processing technology we have developed provides stability and reproducibility of ferroelectric properties.

Figure 2. Press-forms and fabricated disk and substrate samples made of BST-MgO (BSM) ferroelectric. The 110 cm diameter ferroelectric ring for the X-band phase-shifter is shown in the foreground.

We have also performed loss factor measurements of an X-band reflective resonator partially filled with BST-MgO (BSM) ceramic substrate. A 7.8 GHz bulk dielectric resonator has also been measured: both methods yielded loss factors of $(4\text{-}6)\times10^{-3}$ in the (8-12) GHz frequency range with some samples exhibiting smaller values in the $(3\text{-}4)\times10^{-3}$ range. An overall frequency shift of 100-160 MHz of the X-band prototype tunable accelerating structure has been demonstrated over a (1.7-2.5) V/μm range of bias field strengths.

Large BST-MgO ferroelectric ring and tube fabrication

Active high power ferroelectric switches and phase-shifters require large diameter ferroelectric rings with electrical properties similar to those mentioned in the previous section. Recently we fabricated and tested a 110 mm BSM ferroelectric ring (Fig.2**)**. We have also developed an ultra-thin BST ferroelectric tube for a tunable DLA accelerating structure: the required thickness in the 600 micron range has been achieved (Fig.3**)**.

Homogenization theory of the BST-MgO composition material

Analytic and numerical homogeneous 2D models of the BST-MgO composite material have been developed [5]. An important result of this analysis shows that the tunability of the composite medium does not necessarily decrease as the proportion of the linear dielectric component is increased, a result in agreement with our measurements of BSM composites. This in turn offers the possibility of synthesizing a nonlinear composite with high tunability but significantly reduced loss factors.

Figure 3. Ceramic waveguide layer made of BST-MgO (BSM) ferroelectric with wall thickness 600 μm, diameter 10 mm and length of 4.5 cm. The sample was fabricated for the 11.424 GHz tunable DLA structure project.

SUMMARY

We have developed new ferroelectric materials with applications to tuning and switching accelerator components. The bulk BST-MgO composition has been identified as the best candidate for use in these devices. The dielectric constant of the material is in the range of 400-500, the loss tangent at 10 GHz does not exceed (4-6) $\times10^{-3}$ at X-band and Ka band and the tunability factor (dielectric constant relative variation) is in the range of 1.22-1.29 at a 4.5 V/μm (45 kV/cm) dc biasing field. The new BSM ferroelectrics have been studied for use in a fast ferroelectric switch and phase shifter for the LC active pulse compression scheme. Addition of a layer of BSTM ferroelectric allows frequency tuning of dielectric loaded accelerating structures. An overall tuning range of 160 MHz has been demonstrated for the tunable 11.42 GHz DLA structure corresponding to the 1.2 tunability factor of the BST-MgO ferroelectric material.

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