FERROELECTRIC BASED HIGH POWER COMPONENTS FOR L-BAND ACCELERATOR APPLICATIONS*

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Abstract

Euclid TechLabs LLC is developing BST based ferroelectric elements designed to be used as the basis for new advanced accelerator components operating in the 1.3 GHz frequency range and intended for Project X and ILC applications. These new ferroelectric elements are designed for the fast active tuner for SC cavities that can operate in air at low biasing DC fields in the range of 15 kV/cm. The BST(M) material (BST ferroelectric with Mg-based additives) allows fast switching and tuning both in vacuum and in air: a switching time < 10 ns of material samples has been demonstrated. The overall goal of the program was to design an L-band externally-controlled fast ferroelectric tuner for controlling the coupling of superconducting RF cavities for future linear colliders. The tuner prototype has been built; a time response of <30 ns, or 1 deg. in 0.5 ns has been reached. The following problems are addressed: (i) lowering the losses in the ferroelectric material; (ii) improving the technique of the ferroelectric element metallization and brazing; and (iii) improvement of the breakdown threshold at high voltage bias.

INTRODUCTION

Ferroelectrics have unique intrinsic properties that make them extremely attractive for high-energy accelerator applications [1]. Typical representative ferroelectric materials are $BaTiO_3$ or a $BaTiO_3$ - $SrTiO_3$ solid solution (BST) that can be synthesized in the form of polycrystalline ceramic layers and in bulk [1,6].

Euclid Techlabs LLC developed the BST(M) material (BST ferroelectric with Mg-based additives) in 2005-2007 that allows fast switching and tuning in vacuum at a high bias voltage of 50 kV/cm [2,8]. This material was developed for the X-band frequency range (11.424 GHz) and demonstrated loss tangents as low as $\tan\delta = 5\times10^{-3}$ at 10 GHz. Tunability, time response and loss factor measurements for large bulk ferroelectric samples have been done by Omega-P, Inc./Yale University, and these results have been recently published [7].

The overall goal of the current program was to design an L-band externally-controlled fast ferroelectric tuner for controlling the coupling of superconducting RF cavities for the ILC and Project X [7,8,9,10]. The tuner prototype has been built and experimentally demonstrated by Omega-P, Inc. using ferroelectric bars developed by Euclid Techlabs; a time response of <30 ns has been demonstrated [7]. The recently proposed planar tuner design [7] requires new elements to be developed made of an improved new ferroelectric material with a reduced loss tangent [8].

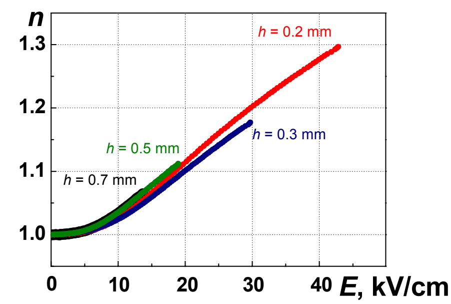

Figure 1: BST(M) ferroelectric tunability dependence on the DC field magnitude.

The principal goal of this project is to develop new BST-based elements, HV-proof with a robust gold deposition providing solid DC bias contacts, and dielectric constant tuning in the range of 5-6% at 15 kV/m electric field. The field can be applied in air. The brazing technology providing HV joints from the gold layers deposited on the ferroelectric surface to the HV bias field copper contacts are being developed along with HV triple point protection. The latter prevents HV discharge in air at 15 kV/cm bias fields. The ultimate aim of the project is to demonstrate experimentally BST(M) elements and test these L-band ferroelectric active phase shifting and control elements for accelerator devices at high power.

BST FERROELECTRICS AS TUNING ELEMENTS FOR 1.3 GHZ SC CAVITIES

1.3 GHz Tuner for ILC and Project X

The RF system for the ILC includes about 16,000 one-meter long 9-cell superconducting cavities. The RF power is generated by 560 klystrons per linac, each feeding 28 nine-cell cavities [10]. The required peak power per klystron is about 10 MW, including a 10% overhead for correcting phase errors during the beam pulse which arise from Lorentz force detuning and microphonics. Severe requirements exist for stability of RF phase during the pulse in the ILC acceleration sections: the r.m.s. phase deviation should be no greater than 0.4° [10].

There are two strategies that can be used in order to confront problems caused by microphonics and Lorentz

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forces. The first is to apply an active correction to the cavity dimensions using a piezoelectric (or magnetostrictive) frequency tuner. A second means for neutralizing microphonics and Lorentz force effects is to use an external tuner to apply a corrective phase shift to the reflected RF wave and reintroduce it to the cavity structure. Using the piezoelectric tuner requires cryogenic temperatures and thus permits only limited access inside the cryomodule in the event of a failure. The second strategy of using an external tuner has been studied with ferrite tuners that are currently being developed at CERN and [11] and tested recently at Fermilab [12]. It may be important that an external tuner allows compensation of the phase errors caused by the power distribution system. However, ILC has a stringent requirement for amplitude and phase stability. Thus, the gain in the control feedback loop must be high enough, and its bandwidth wide enough, to insure this high degree of stability. This may rule out ferrite tuners with their narrow bandwidth.

Project X is a concept for a high-intensity proton accelerator facility exploiting technology developed for the ILC [9]. The linac utilizes technology in common with the ILC over the energy range 0.6 – 8.0 GeV. Beam current parameters can be made identical to those of the ILC resulting in identical rf generation and distribution systems [9]. The Project X power distribution scheme will require adjusting the power, Q_{ext} and phase for each cavity to achieve a flat gradient distribution in each cavity. One needs to moderate the RF amplitude (1%) and phase (1 degree) regulation and slow phase and Q_{ext} control to meet the 8 GeV beam specification. The current design may require power, Q and phase control between pulses and power, Q and/or phase control during beam propagation [9]. The need to modify the RF distribution system will also require an additional component, a fast tuner, to be developed [7].

The Omega-P, Inc. and Euclid Techlabs SBIR program in collaboration with FNAL and ANL has as its goal the design of a fast electrically-controlled L-band tuner with a ferroelectric phase shifter [7,8] that has parameters suitable for ILC and Project X applications. The ferroelectric tuner will compensate phase errors in real time so as to provide the required phase stability. In addition, this tuner allows programmed coupling changes during the cavity filling process that can provide significant AC power savings of about 8 MW, or 4% of the entire power consumption of the ILC [7].

Ferroelectric Material for the BST-based Fast Tuner

Ferroelectrics have an **E**-field-dependent dielectric permittivity **ε** that can be very rapidly altered by application of a bias voltage pulse [1,6]. The switching time in most instances will be limited by the response time of the external electronic circuit that generates and transmits the high-voltage pulse, and can therefore be in the nanosecond range [1].

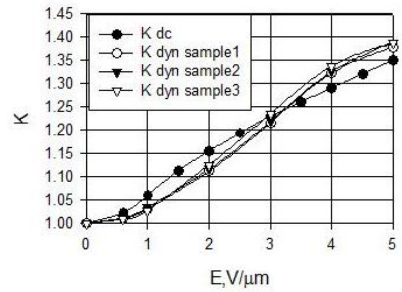
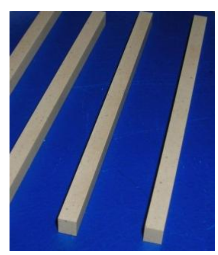


Figure 2: Example of DC tunability K_{dc} and dynamic (short ~ns pulse) tunability K_{dyn} for different compositions of BST(M) ferroelectric. Note that for a bias field > 3 V/µm (30 kV/cm) $K_{dyn} > K_{dc}$.

Ferroelectric materials should have the following properties in order to be used for high power RF management in accelerator applications [2,3]: (1) the dielectric constant should not exceed 150-500 to avoid problems in the switch design caused by interference from high-order modes; (2) the dielectric constant should be variable by 6% or more to provide the required tuning properties; (3) the bias electric field required to adjust the permittivity within this range should be reasonable (~15kV/cm) providing tuning operations in air; (4) the loss tangent should be $<1\times10^{-3}$ at 1.3 GHz [2,3].



(a)

(b)

Figure 3**:** (a) BST(M) ferroelectric bar samples fabricated for a 1.3 GHz planar phase shifter; (b) BST(M) ferroelectric ring sample. The ring diameter is 110 mm, and its thickness is 2.8 mm.

Sintering of large BST ferroelectric components is a key issue for ferroelectric based L-band tuner fabrication. Initial samples of BST(M)-type ceramic materials studied in this work are powders with particle size ~ 1 µm based on solid solutions of barium/strontium titanates with magnesia-based additives. The composition of these powders as well as their processing technology provides the option of using various methods of forming half-finished products that are widely used in ceramic technology. These are primarily methods of hydraulic and isostatic pressing used for ceramic pre-forms in cylindrical geometries of various lengths and cross-sections.

Tunability is the capability of controlling changes of the dielectric constant by applying a constant bias electric field to ferroelectrics in a paraelectric phase, $n=\varepsilon(0)/\varepsilon(E)$ [1]. Euclid Techlabs LLC recently developed and tested a modified bulk ferroelectric operating in vacuum [2,8]. This material is based on a composition of BST ceramics and magnesium based compounds that has a permittivity ε = 500-600, and 25-35% change in permittivity for a bias electric field of 50 kV/cm, Fig.1. The loss tangent currently achieved is less than 5×10^{-3} at 11.4 GHz. Development of production techniques for new materials with ε~ 150-500 continues, with the expectation of enabling in air operations at a 15 kV/cm field and of lowering the loss tangent to values $<1\times10^{-3}$ [8].

It is possible to use BST/Mg-additive composites to produce ferroelectrics with a value of ε in the range of 200-300 and lower. However, in this case the tunability of ε by a DC field is sharply reduced and becomes negligibly small, especially with a small bias voltage of the order of 10-20 kV/cm. The use of the magnesium orthotitanate additive leads to the increase of the tunability coefficient $n=\varepsilon(0)/\varepsilon(E)$, Fig.1 [8]. It is especially important that such compositions demonstrate high dynamic tunability K_{dyn} when applying short pulses at relatively low DC fields ~15 kV/cm. Our measurements showed that in this case K_{dyn} may even exceed K_{dc}, Fig. 2. These differences, as the measurement data show, are especially significant for samples of BST compositions with increased concentrations of the Mg_2TiO_4 additive (more than 40% by mass) operating in the high biasing field range exceeding 30 kV/cm.

Time response of the pure BST ferroelectric is $\sim10^{-11}$s [1,6] and this parameter for the tunable elements is defined at L-band frequencies by the design of the device and the configuration of the metal electrodes [5]. A <10 ns time response for bulk BST(M) ferroelectric samples with gold electrodes has been demonstrated recently at L-band by Euclid Techlabs LLC.

Ferroelectric Based Tuner Designs

A preliminary design of a fast external tuner for coupling of ILC cavities using electrically-controlled ferroelectric phase shifters was proposed by Omega-P, Inc. [3]. The BST ferroelectric rings of 100 mm diameter and 2 mm thickness were used for this design. Each tuner should allow rapid changes in the coupling of an ILC cavity with the feed line at a pulse power level of up to 500 kW and average power of 4 kW. The ferroelectric ring element for this design is shown in Fig. 3b.

A new simpler planar design of the ferroelectric phase shifter suitable for SC RF systems and ILC applications has been considered as well [7]. The phase shifter contains three sections. Each section contains four ferroelectric bars, Fig.3(a), located on the intermediate electrodes with rounded corners, where the bias field is applied. Each section transmits 1/3 of the entire power flow that reduces the RF fields to acceptable levels for air operation [7].

Fast Time Response

Measurements of response time were made**.** 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. 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 approximately 30 ns, corresponding to an average switching rate of less than 0.5 ns for each degree of RF phase [7].

SUMMARY

A BST(M) composition material operating in air in the L-band frequency range has been developed for use as a ferroelectric active phase shifting and control elements for accelerator devices. The current research program includes: (1) development and laboratory demonstration of a BST composition bulk ferroelectric with dielectric constant of 300-500, loss factor of $<1\times10^{-3}$ at 1.3 GHz, tunability of 6% at 1.5 V/μm bias field; (2) demonstration of robust gold layer deposition on the polished BST(M) ferroelectric surface; (3) demonstration of the brazing technology to provide the HV joint between the gold deposited on the ferroelectric surface and the HV bias field copper contacts; (4) development of test samples with HV triple point protection to prevent HV discharge in air at 15 kV/cm bias field (5) HV high power experimental demonstration of a 1/3 scale model of the BST(M) ferroelectric based fast L-band tuner (in cooperation with Omega-P, Inc. and FNAL).

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