FERROELECTRIC BASED TECHNOLOGIES FOR ACCELERATOR COMPONENT APPLICATIONS*

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Abstract

We present recent results on development of BST(M) ferroelectric compositions synthesized for use in advanced technology components for X-band and Ka-band RF systems in high gradient accelerators and offer significant advantages for high power RF manipulation in the 300-1000 MHz frequency range as well. These low loss ferroelectric materials can be used as key elements of both tuning and phase shifting components. We have identified BST ferroelectric-oxide compounds as suitable materials for a fast electrically-controlled 700 MHz, 50 kW tuner for ERL (BNL) and for high-power fast RF phase shifters to be used for SNS vector modulation applications. We have also developed large diameter (11 cm) BST(M)-based ferroelectric rings planned to be used at high average power (10 kW range) for L-band phase-shifters intended for the ILC. This phase shifter will allow coupling adjustment and control of the power consumption during the process of SC cavity filling.

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 and tuning devices intended for accelerator applications [1-3].

We have identified BST ferroelectric-oxide compounds as suitable materials for the accelerator components. A BST(M) ferroelectric that is a BST material with Mg-based additives has been developed [4-6]. The relative dielectric constant ε can be tuned in the range of 300 - 500. We have developed and improved the ferroelectric $Ba_xSr_{1-x}TiO_3$ (BST) with Mg-based additives to achieve loss tangent parameters in the $(3\text{-}4)\times 10^{-3}$ range at 11.4 GHz.

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Critical technologies relevant to the development of nonlinear ferroelectric compositions to be used in accelerator physics have been demonstrated recently [4-6]: (1) experimental study of the phase composition and structure of test samples depending on the solid solution compound, the raw materials and synthesis technique; (2) development of the homogenization theory of the hetero-composition of BST with Mg-based additives, and a 2-D model simulation of the tunability for this material; (3) fabrication of samples of BST material required for 3-35 GHz dielectric property measurements; (4) measurement of the dielectric response of the material in the (3-12) GHz and 35 GHz frequency ranges; (5) development of forming and sintering technology for large BST ferroelectric components. Large diameter rings (5-11 cm) have been manufactured and demonstrated for accelerator applications [4,5,7].

BST(M) FERROELECTRIC COMPONENT STUDIES

Tunability. Dimension Effects

The dimension effect has been studied in this project. We observed that a thin 200 μm sample showed the best absolute tunability n of 1.29 % at 4.5 V/μm bias field E (note that $n = \varepsilon(0)/\varepsilon(E)$). Recently we have studied the tunability factor and processing time of the dc bias voltage versus sample thickness over a 0.2-3.0 mm range.

Fig. 1 and Fig. 2 present the results of the size effect studies for the tunability factor of the BST(M)-3 and BST(M)-4 samples for thicknesses in the h = 0.1-0.7 mm range.

The n = f(E) dependences for all of the samples are nonlinear in the range of small magnitudes of the applied biasing electric fields, defined by the nonlinear behavior of the corresponding current-voltage characteristics. For the thin samples of the same thickness h~0.1mm of BST(M)3 and BST(M)4 ferroelectric the onset of nonlinearity is around E< 2 V/μm. The thick h = 0.7 mm samples demonstrated the same nonlinear behavior in the biasing field range of E< 0.8 V/μm according to our estimates.

If the biasing field E exceeds 2 V/μm, the tunability factor vs. field magnitude is almost linear, cf. Fig. 1 and Fig. 2. The dispersion in tunability factor for the samples with different thicknesses has been indicated mostly for the BSM-3 ferroelectric ceramic. The samples made of BSM-4 ceramic show almost identical tunability factor,

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with the n = f(E) lines closer to each other as shown in Fig. 2.

The large dots presented in Fig. 1and Fig. 2 correspond to the 3 mm thick samples measured at 2.5 GHz. The dots with field magnitude ~1.3 V/μm were obtained experimentally and the E = 2 V/μm biasing field points were extrapolated.

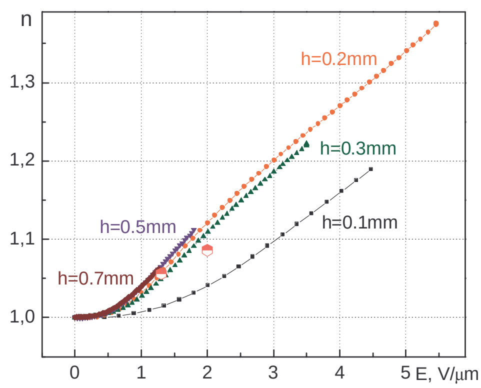

Figure 1. Size effect studies for the BST(M)3 ferroelectric samples with thickness in the 0.1 – 0.5 mm range. The behavior becomes nonlinear for biasing field magnitudes < 2 V/μm.

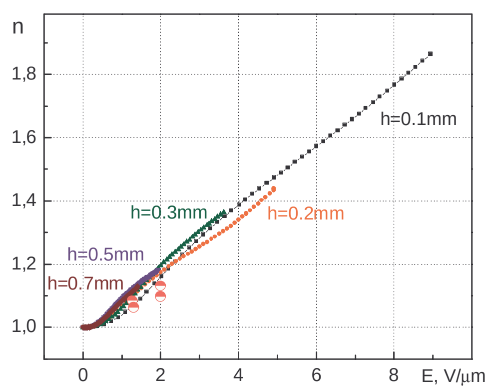

Figure 2. Size effect studies for the BSM-4 ferroelectric samples with thicknesses of 0.1 – 0.5 mm. One can see the nonlinear curve behavior for biasing field magnitude < 1 V/μm that is critical for L-band applications.

For this set of measurements, the minimum influence of size effects (and the electrode sublayer contribution) have been obtained for the BSM-4 samples. The maximum tunability factor for the same group of samples is in the range of n = 1.86 at E = 8.94 V/μm bias field magnitude. Note the BST(M)4 material has been developed for L-band applications where linearity n = f(E) is important, above 1 V/μm.

Dielectric Response Measurements.

We have studied the dielectric response of the BST(M)-3 and BST(M)-4 materials proposed for accelerator applications. The dielectric constant of the BST(M)-3 ferroelectric is ~550-590, while the loss tangent was found to be in the 5.6-6.6×10^{-3} range at 10 GHz, Q×f=1500-1800 GHz (note that Q~1/tanδ and for the BST(M) material tan δ~f in the frequency ranges considered). The best sample demonstrated a loss tangent of 4.8×10^{-3} at 10 GHz. BST(M)-4 material shows a higher tunability than BST(M)-3 while keeping Q×f in the range of 750-1100 GHz. This material is currently under development to improve its loss tangent. The frequency dependence of the dielectric constant and Q×f parameter characterizing the material loss tangent are presented in Fig. 3. One can see the flat behavior of the dielectric response vs. frequency of the BST(M) group of materials that makes this ferroelectric usable for L-band and X-band high power applications. Ka-band measurements are currently planned.

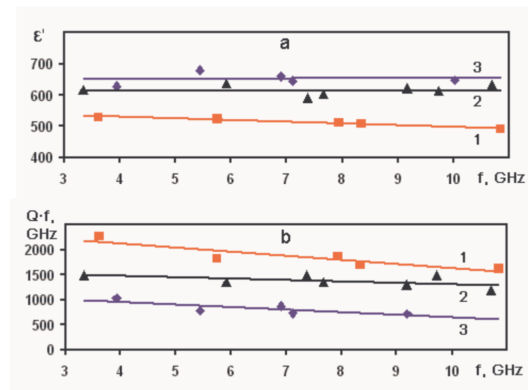

Figure 3. Frequency dependence of ε′ (a) and Q·f (b) for ceramic samples: (1) – BST(M)1; (2) – BST(M)3; (3) – BST(M)4

Ferroelectric Microstructure Studies

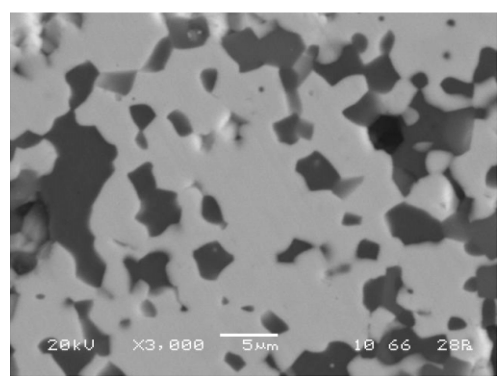

Figure 4. SEM image of a BST(M)3 ferroelectric sample sintered at 1400°C

SEM imaging shows that the Mg-based additives do not dissolve in the BST main phase and were found to be combined in a hetero-mixture phase. Basic phases are the (Ba,Sr) TiO_3 (BST) solid solution and the magnesia-based phase. Some additional phases have been found in the phase composition of the samples. This amount can attain 3-5% or less and may significantly influence the level of dielectric losses of the ceramic ferroelectrics. Fig. 4

presents an SEM image of a BST(M)-3 sample sintered at 1400°C. One can see that the sample has two main phases indicated by different contrasts: light and dark-grey. Based on X-ray spectra simulations the light phase corresponds to $(Ba,Sr)TiO_3$ and the dark-grey phase corresponds to the Mg-based additives.

Ferroelectric-Based High Power Component Fabrication

Optimization of the production technology for ceramic ring pre-forms ~100 mm in diameter and 20 mm high together with methods of their mechanical treatment that enable production of rings 3-5 mm thick have been carried out using fine ceramics based on hydrothermal barium titanate.

Figure 5. Large-diameter ceramic ring samples made of BST(M)3 ferroelectric. The ring diameter is 104.2 mm and the ring thickness is 2.6 mm.

We have developed large diameter rings made of BST(M)3 ferroelectric. The gold metallization for supplying the bias voltage has been deposited as well; the surface finish and corresponding adhesion have been studied and tested.

Two main compositions of the BST(M) ferroelectric material were considered for ferroelectric ring fabrication, ε=500-530 and ε=550-600. The ring thickness is 2.6 mm for ε=550, with the inner diameter 104.2 mm, Fig. 5.

Currently four gold metallized test rings made of BST(M)3 ferroelectric with the surface finish of required quality have been developed and are being tested by Omega-P, Inc.; the measurement results are presented in [7].

Transverse and parallel bias dc field studies.

The concept of the transverse dc bias field is considered for applications to tunable high power accelerator components. The BST(M)3 dielectric-ferroelectric composite has been studied experimentally with respect to the dielectric response on applied transverse and parallel bias fields. The absolute tunability vs. transverse and parallel biasing voltages has been measured. Data comparison between the experimental studies and analytical simulation of both pure BST ferroelectric and dielectric-ferroelectric BST(M)-3 composites has been carried out.

The absolute tunability measurements performed for the BST(M)-3 composite have demonstrated a tunability factor corresponding to the required values of 1.13-1.16 for a 40—50 kV/cm dc biasing field. Feasibility of the use of transverse bias configurations for ferroelectric based accelerator component tuning has been demonstrated with this experiment. Meanwhile, with parallel biasing fields, the BST(M)-3 ferroelectric-dielectric composite showed tunability factors in the range of 1.25-1.28 at a 40—50 kV/cm dc biasing field.

SUMMARY

As a result of the microstructure and dielectric response studies of the BST-based ferroelectric material with Ba/Sr ratios in the range of 55/45 and 60/40, and Mg-content additives, the BST(M) group of materials have been developed. We have studied the dielectric response of the BST(M)-3 material proposed for accelerator applications. The permittivity of the BST(M)-3 ferroelectric is 550-590, while the loss tangent was found to be in the range of $5.6\text{-}6.6\times10^{-3}$ at 10 GHz, Q×f=1500-1800 GHz. The frequency dependence of the dielectric response of BST(M)3 ceramic has been measured at L-band and X-band frequency ranges. We have studied BST(M) microstructure and microwave properties over a wide range of ferroelectric parameters and compositions. We have studied size effects in the developed group of materials. The BST(M) ferroelectrics have been tested using a transverse dc bias field. The tunability factor vs. dc field magnitude has been evaluated for these newly developed materials. The feasibility of transverse bias tuning for ferroelectric based accelerator components has been demonstrated. Finally, we have accomplished large diameter ring fabrication using BST(M) ferroelectric ceramic and tested the gold deposition technology for bias electrodes on the BST rings.

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