TUNABLE FERROELECTRIC BASED TECHNOLOGIES FOR ACCELERATOR COMPONENTS*

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Abstract

Low loss ferroelectric materials can be used as key elements in RF tuning and phase shifting components to provide fast, electronic control. These devices are under development for different accelerator applications in X, Ka and L - frequency bands. The exact design of these devices depends on the electrical parameters of the particular ferroelectric material to be used- its dielectric constant, loss tangent and tunability. BST based ferroelectric-oxide compounds have been found to be suitable materials for a fast electrically-controlled tuner for BNL and for high-power fast RF phase shifters to be used for SNS vector modulation applications. We present recent results on the development of BST based ferroelectric compositions synthesized for use in high power technology components operating in air. The BST(M) ferroelectrics have been tested using a transverse and parallel dc bias fields. The tunability factor vs. dc field magnitude has been evaluated and the feasibility of transverse bias tuning for ferroelectric based accelerator components has been demonstrated.

INTRODUCTION

Ferroelectrics have unique intrinsic properties that make them extremely attractive for high-energy accelerator applications. Their response time is $\sim10^{-11}$ sec for crystalline and $\sim10^{-10}$ sec for ceramic compounds. High dielectric breakdown strength, low gas permeability and easy mechanical treatment make ferroelectric ceramics promising candidates for the loading material in tuning and switching RF devices for accelerator applications. Typical representative ferroelectric materials are $BaTiO_3$ or a $BaTiO_3$ - $SrTiO_3$ solid solution (BST). The BST solid solution can be synthesized in the form of polycrystalline ceramic layers and in bulk [1].

Euclid developed in 2005-2007 the BSM-3 material (BST ferroelectric with Mg-based additives) that allows fast switching and tuning *in vacuum* at a high biasing voltage of 50 kV/cm [2-3]. 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 and loss factor measurements for large bulk ferroelectric samples have been done by Omega-P, Inc./Yale University, and these results have been presented and published at PAC2007 [3].

The principal goal of this work is to develop a new BST-based material with a tunability of 6-8% at 15 kV/cm biasing field to be applied *in air*. Development of this type of material is a challenge: the tuning behavior of the dielectric constant should be appreciable. At the same time, optimized Ba/Sr ratios could in principle enhance the tunability of the entire composition but the loss factor increases as well prohibiting the use of this ferroelectric at high frequencies due to the high power absorption.

ACCELERATOR APPLICATIONS OF THE BST(M) FERROELECTRIC MATERIAL

A significant luminosity enhancement can be obtained for the full range of ions used at RHIC at energies of up to 100 GeV/A. This requires a high-current, high-bunch charge low emittance ERL (energy recovery linac) for the electrons used for beam cooling. Omega-P Inc/Yale University in collaboration with Euclid Techlabs LLC recently proposed a program that has as one of its goals the design and development of a fast electrically-controlled 700 MHz, 50 kW tuner based on a ferroelectric phase shifter for ERL applications [3]. The phase shifter will allow coupling adjustment and control of the power consumption during the cavity filling. The tuner implementation will allow significant reduction of the power required from the RF source for linac operations.

A fast ferroelectric phase shifter controlled by a bias electric field is being investigated by the Accelerator RF Group of the SNS to be used for vector modulation [4]. The use of BST compounds has been investigated in a coaxial phase shifter prototype for frequencies in the 300 MHz – 1300 MHz range that could be adapted for future large-scale accelerator projects. Other critical accelerator applications in X-band and K/Ka band frequency ranges can be found in [2-3] and references there.

BST(M) FERROELECTRIC COMPOSITION OPERATING IN AIR

We consider the design of the tunable low-loss material intended to be used in devices open to the air. It was demonstrated recently that by introducing linear (non-tunable) Mg-based ceramic into the BST solid solution one can enhance the tunability factor of the entire composition while keeping the loss tangent below 10^{-3} at

1.3 GHz [2-3]. These completely counterintuitive properties (by increasing of non-tunable ceramic content of the ferroelectric-ceramic mixture one can enhance, in turn, the tunability of the resulting material!) opens important new possibilities in designing the specific class of microwave ceramic materials that will enable tuning at low magnitude biasing fields. Using this new approach we have increased the tunability of BSM ferroelectric from 2% to 4% during the course of our preliminary research. This opens a new theoretical and experimental area of studies in ferroelectric science as well as possessing straightforward applications in accelerator physics.

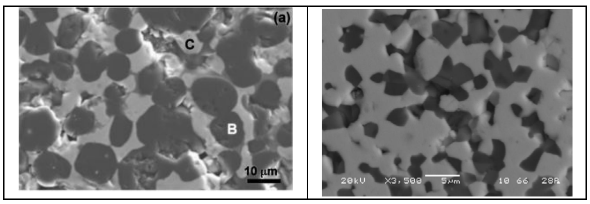

Figure 1: Special features of formation and distribution of the phases of the BST-Mg based additives. (a) BST-MgO crystalline aggregates distributed mostly in the form of separate inclusions [5]; (b) BSM-3 composition, crystalline aggregates are of a sufficiently extended type (for the cross-section of the composite, see Fig.2).

It is known that adding magnesia (MgO) and/or $MgTiO_3$ to the BST solid solutions leads to the formation of a mechanical mixture of initial phases that weakly interact with the BST solid solution at the sintering temperatures of the ceramics. (MgO) and/or $MgTiO_3$ are linear dielectrics with $\varepsilon \approx 9.8$ and 17, $\tan\delta \approx 1{\cdot}10^{-4}$ and $2{\cdot}10^{-4}$ at 10 GHz respectively. It is possible to use BST-MgO and BST-MgO-$MgTiO_3$ composites to produce ferroelectrics with a value of ε in the range of 200-300 and lower. However, in this case tunability of ε by DC field is sharply reduced and becomes negligibly small, especially with a small biasing voltage of the order of 10-20 kV/cm.

At the same time, other additions can be used to improve the discussed composition. In some specific cases, an increase in the content of this linear dielectric in the volume of the composite results in the increase of the tunability coefficient K_{dc}, which is completely unusual. K_{dc} increases almost by a factor of two with the increase of the percentage of the new additive to 60 wt.%. It is especially important that such compositions demonstrate high tunability when applying short pulses K_{dyn} at relatively low DC fields ~15 kV/cm. Our measurements showed that in this case K_{dyn} may even exceed K_{dc}. These differences, as the measurement data showed, are especially significant for samples of BST compositions with increased concentration of the additive (more than 40 mass%) operating in the high biasing field range exceeding 30 kV/cm.

Investigations of phase composition and microstructure conducted in our work revealed a number of special features of formation and distribution of the phases that appear, which made it possible to formulate certain models for theoretical analysis [6].

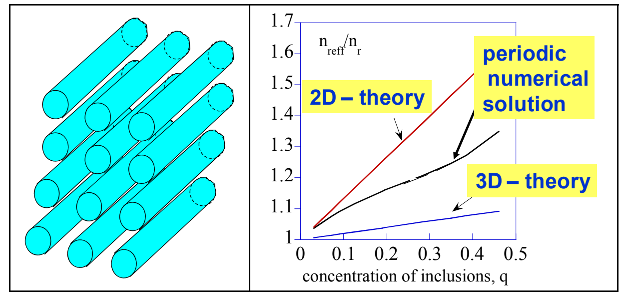

Figure 2: 3D and 2D theoretical model and periodic numerical solution results on the tunability gain vs. concentration of inclusions q.

As the studies showed, the additives that we developed form crystalline aggregates within the BST composition. These aggregates are of a sufficiently extended type (rod-like) [6], in contrast to the traditional magnesia additive, which is distributed mostly in the form of separate inclusions of nearly round (ball-like) sections [5]. This is evident from the comparison of Fig.1 (right) showing a typical micrograph of the structure of ceramics that we developed, and Fig.4 (left) showing the micrograph taken from [5] for the BST composite with magnesia additive. Calculations carried out by the group of Tagantsev within the framework of our studies theoretically confirmed the possibility of an increase in the coefficient of tunability of the dielectric constant for samples with a distribution of the linear dielectric additive in the form of elongated inclusions (Fig.2). This correlates with the experimental data. Fig. 2 also shows that the tunability factor can be increased further by increasing the concentration of the linear dielectric in a composition with the extended type of inclusions.

As these studies showed, such compositions are most promising for use in L-band devices that work in air, since it demonstrated a larger increase in tunability with an increase of the biasing voltage. This is especially important for the use of ferroelectrics in the region of low biasing fields < 20 kV/cm, where the increase in the tunability strongly lags behind the increase in the voltage [3,7].

Meanwhile, as our studies have shown, the use of only one new additive in the BST compositions is accompanied with an increase of $\tan\delta$ of the samples. To decrease the level of the dielectric losses in the ferroelectrics, within the framework of the completed project we used complex magnesium-containing additives. The use of such complex additives in the amount of 25-30 mass% allowed us to decrease the value of $\tan\delta$ for the samples of ferroelectrics with ε~500-600 down to the value of the order of 0.004-0.006 at the frequency of ~10 GHz while maintaining the given tunability. The same approach can be used for L band.

Sintering of large BST ferroelectric components is a key issue for ferroelectric based L-band tuner fabrication. Recently, we have designed and manufactured 10.6-10.8 cm diameter BST(M) ferroelectric rings to be used as switching elements for X-band accelerator applications [2-3]. We have demonstrated that comparatively large planar objects can be formed and sintered out of BST(M) bulk material. 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 [2-3].

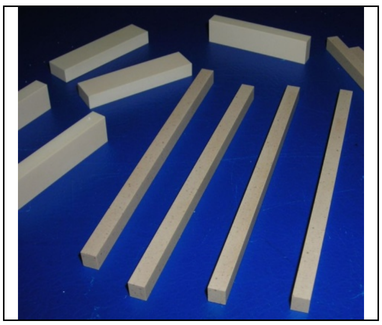

Figure 3: BST(M) ferroelectric bars and forsterite plates fabricated for the fast L-band tuner development [7].

A specially developed technology of double layer magnetron metal deposition has been used to apply the gold contacts for the bias voltage. This technology allows deposition of a 1-2 um thick gold layer on a sub-layer at the ferroelectric surface providing an adhesion satisfying the mechanical requirements of the device.

The BST(M) ferroelectric bars have been fabricated for the fast L-band tuner [7]. Fig. 3 shows a set of the BST bars and forsterite plates for the tuner prototype test before assembly. The bar cross-section is 5.1×6.0 mm and length 108 mm. Linear ceramic plate dimensions are 11.15×6.0 ×47.0 mm, dielectric constant of 21.

A planar design of the fast phase shifter has been developed using ferroelectric elements shown in Fig.3. Recent experimental tests show that the device provides a phase shift of 120° without air breakdown, and with an insertion loss of -0.64 dB [7].

The tunability factor was found in our preliminary measurements to be in the range of 4% at 15 kV/cm dc bias field with a quality factor of Q×f= 700-900 and promising Q×f=1400 demonstrated with the best samples.

The concept of the transverse dc bias field is considered for applications to tunable high power accelerator components as well. The newly developed BST(M) dielectric-ferroelectric composite has been studied experimentally with respect to the dielectric response to applied transverse and parallel bias fields. The absolute tunability vs. transverse and parallel biasing voltages has been measured. Comparison between the experimental studies and analytical simulation of both pure BST ferroelectric and dielectric-ferroelectric BST(M) composites has been carried out based on a theory developed recently by Tagantsev [8]. Our experimental and theoretical results are presented in Fig. 4.

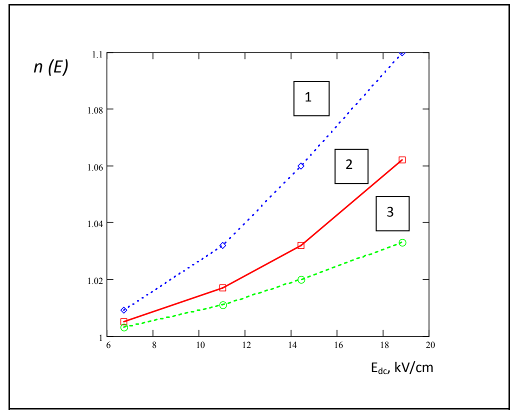

Figure 4: Studies of the BST(M)-3 ferroelectric material developed by the Euclid/Ceramics Company Ltd. collaboration for tunable high voltage accelerator components. The curves show tunability measurements for (1) parallel bias field (2) the transverse bias field; and (3) theoretical minimum expected transverse tunability [8].

SUMMARY

A BST(M) composition material operating in air in the L-band range has been developed for use as a ferroelectric active phase shifting and control elements for accelerator devices. We have studied the microstructure and dielectric response of the new BST-based ferroelectric material over a wide range of ferroelectric parameters and compositions. The BST(M) ferroelectrics have been tested using parallel and transverse dc bias fields. Finally, we have accomplished fabrication of bulk ferroelectric bars using the BST(M) ceramic. The gold deposition technology for bias electrodes on the BST components has been experimentally tested as well [7].

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