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

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Abstract

With this paper, we present our recent results with a new fast ferroelectric tuner development. The tuner is based on BST(M) ferroelectric elements (ε~150), which are designed to be used as the basis for L-band accelerator components intended for ERL, ILC, Project X and other applications. These new ferroelectric elements are to be fabricated for the new fast active tuner for SC cavities that can operate in air at low biasing DC fields. Specific features of ERL, ILC and Project X accelerator technology and challenges of the designs are high magnitude and phase stability of its operations. Mechanical vibrations, or microphonics affect the SRF resonator, while the ferroelectric tuners have shown extremely high tuning speed. We have demonstrated successful mitigation of the residual effects on the ferroelectric-metal interface along with the acceptable level of the overall loss factor of the tuner element. A new concepts of a phase shifter based on low dielectric constant ferroelectric elements, fabrication technology of these new BST(M) ferroelectric elements are presented.

INTRODUCTION

With this paper, we consider development of new fast tuners based on low dielectric constant ferroelectric elements (ε~100-150), and fabrication of these BST (barium strontium titanate) [1,2] based ferroelectric elements that are designed to be used as the basis for new advanced accelerator components operating in the 0.7-1.3 GHz frequency range and intended for ILC [3], Project X [4,5] and ERL [6] applications. These new ferroelectric elements developed for a new fast active tuner for SC cavities that can operate in air at low biasing dc fields on the order of 15 kV/cm. Specific features of ERL (Energy Recovery Linac) accelerator technology and the challenges of ERL designs for X-ray light sources are the high magnitude and phase stability of its operations, in the range of 3×10^{-4} and 0.06 degree respectively [7]. At the same time, mechanical vibrations (microphonics) contaminate the resonator frequency with characteristic frequencies in the range of 100 Hz [8]. Ferroelectric tuners have demonstrated extremely high tuning speeds [9-10] and this concept is promising for accelerator systems where high frequency tuning is an ultimate goal. The ERL technology requires exactly the same type of fast tuner [9].

Note that the fast ferroelectric tuner would find widespread applications for superconducting cavity stabilization. For example, it would be very useful in the case when a number of cavities are fed by a single rf source, as in the Project X pulsed linac [4,5]. In this case, the tuner will provide independent amplitude and phase control of the field in separate cavities, a capability that may be especially important for proton linacs.

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 [1,2]. 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 [1,2].

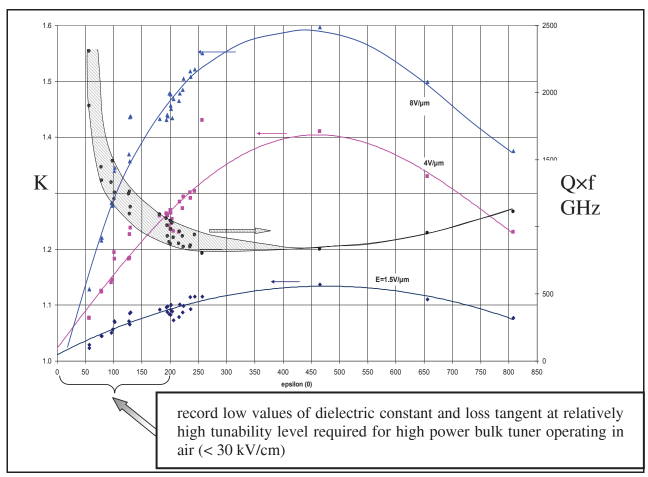


Figure 1: BST(M) ferroelectric tunability dependence on the DC field magnitude.

Recently a BST(M) material (BST ferroelectric with Mg-based additives) that allows fast switching and tuning *in vacuum* at a high biasing electric field of 50 kV/cm was developed [11-12]. This material was proposeed for the X-band frequency range (11.424 GHz) and demonstrated loss tangents $\tan\delta = 5\times10^{-3}$ at 10 GHz [11]. Tunability, time response and loss factor measurements for large bulk ferroelectric samples developed for operation at L-band in air have been presented and published recently [13-16].

CONCEPTUAL DESIGN OF A MULTI-STAGE COAXIAL TUNER

A new, simpler coaxial tuner design for the ferroelectric phase shifter suitable for SC rf systems, ILC and ERL applications has been studied, Fig. 2. and Fig.3. The phase shifter has a coaxial geometry and consists of two identical ferroelectric elements (rings). The proposed design became feasible only recently (2010) immediately after the first samples of a new low dielectric constant ferroelectric material with dielectric constant in the range of ~100 units and figure of merit $Q \times f$~1500-1700 was developed [15]. Distinct from previously considered designs, use of a low dielectric constant ferroelectric does not require a matching linear dielectric element to be introduced into the tuner design [9,13].

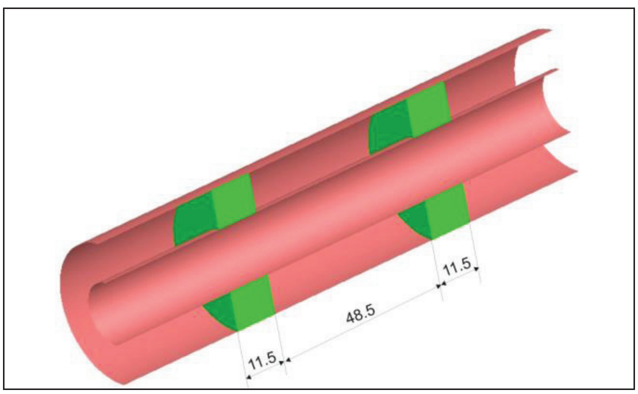
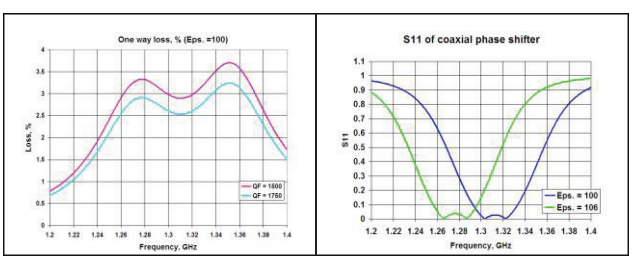


Figure 2: Geometry (units in mm) of the coaxial phase shifter containing two ferroelectric rings with low zero-field dielectric constant ε =100.



(a) (b)

Figure 3: Simulations of loss factor vs. frequency for the coaxial tuner containing two low permittivity ferroelectric rings; (a) phase shift vs. frequency; (b) S11 parameters of the coaxial phase shifter ε =100.

The tuner design consists of two resonators providing the required phase shift. This design has been validated in simulations that show tunability and low stored energy resulting in reduced power loss of the tuner. The simulated loss factor for the current tuner design does not exceed 5-6% for ferroelectric materials with recently demonstrated figures of merit $Q \times f$ =1500-1700, Fig.3.

Reducing the dielectric constant down to ε<100 would allow a further decrease of losses in the tuner to 4.5% for the proposed design. In Fig.4 a 3D model of the phase shifter is shown. Bias voltage is applied to the central electrode. In order to minimize rf leakage through the bias port, a plunger is used. The inner conductor is air cooled. Bellows are used in the central conductor in order to compensate for thermal expansion and protect the ferroelectric ceramic. The ferroelectric ring is brazed to the central conductor and to the copper bushing of the connecting flange.

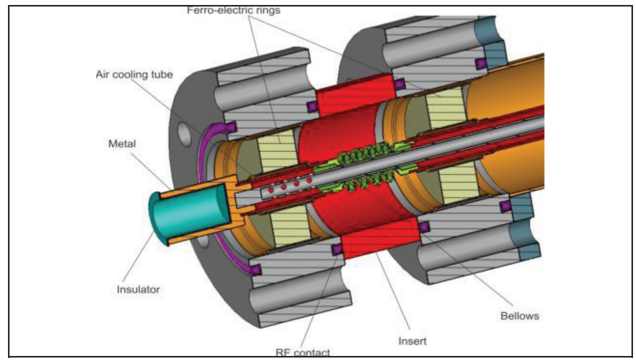


Figure 4: 3D CAD model of the phase shifter.

FERROELECTRIC COMPONENTS

Preliminary research has been done in the development of a new BST-based material with a tunability of 6-8% at a 15 kV/cm biasing field to be applied *in air* [13-16]. It was demonstrated recently that by introducing a linear (non-tunable) Mg-based ceramic component 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 [15]. This completely counterintuitive property (by increasing of non-tunable ceramic content of the ferroelectric-ceramic mixture one can enhance 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. An unprecedented low zero-field permittivity but still tunable nonlinear material – a BST ferroelectric and Mg-based additive composite with a dielectric constant in the range of 60-100 is under development now [13-16].

The main result represents a breakthrough in the technology of ferroelectric materials, specifically in the manufacturing of electrically controllable elements for rf and microwave applications. Previously, the presence of significant residual effects prevented the permittivity of the ferroelectric tuning element from directly tracking the instantaneous bias (control) field. These effects prevent using bulk and thin film ferroelectric elements for the phase-shifting and tuning devices operating in air. We developed a specific annealing process that provides a dramatic reduction of lag or hysteresis in the dielectric response of the nonlinear material caused by relaxation effects. As an added benefit, the same processing

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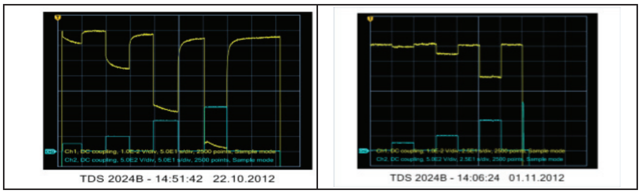
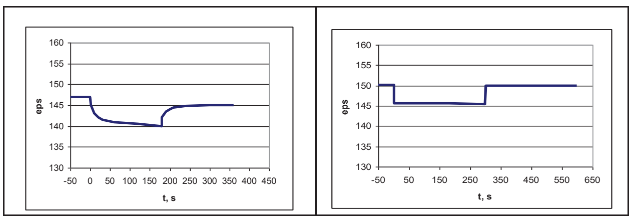
technology ensures that the loss factor of the active tuning element is improved by a factor of ~ 2 in the L-band frequency range.



(a) (b)

Figure 5: Measurement results of the switching time of ferroelectric ceramic samples with Au electrodes deposited; response of the ceramic samples (yellow) to a pulsed electric field (blue): (a) before and (b) after the annealing.



(a) (b)

Figure 6: Dielectric response measurement (dielectric constant) after the rectangular dc bias pulse: (a) before annealing ε~ 150; (b) after annealing.

A high Q test cavity intended for dielectric constant and loss tangent measurements of brazed bulk ferroelectric elements has been fabricated. The test cavity operates in the 400-1600 MHz frequency range with an intrinsic Q factor (if loaded with a lossless ceramic bar of ε =150) in the range of 1000-2000, depending on the mode frequency. Au electrodes were fabricated by vacuum evaporation; the thickness of the layers was 1 μm.

The residual effect can be clearly seen in Fig.5a, where the measurement results for BST(M) sample is presented. This is a sample with the dielectric constant ~150, polished and with Au directly deposited onto the BST(M) surface. Fig.5a shows time domain responses of the ceramic samples to the pulsed electric field. One can see relaxation changes in the dielectric responses (yellow); the bias field pulse shapes do not repeat the response shapes. Long time range residual effects were detected in the ferroelectric bar measurements as well.

Mitigation of residual effects was demonstrated successfully through the use annealing technique. Measurement results of samples at dc voltage are shown in Fig. 5b; response times of the samples on the control field are presented. One can see that annealing suppresses the relaxation processes completely. We also studied of the residual effects of the ferroelectric bulk components (bars) after the metal deposition. We used gold as a deposition material for the contacts of the BST(M) tuning elements. The results of the dielectric response of the bars on the pulsed dc bias field of 1 V/μm magnitude are presented in Fig. 6. with the permittivity range ε~ 150; Fig.6 presents the bias voltage time response (permittivity) after the dc bias pulse injection, Fig.6a - before the annealing, ε=147; Fig.6b - after the annealing, ε=150. Note there were almost no residual effects after the annealing.

SUMMARY

We proposed a new fast solid state microwave tuner design. The device is based on low permittivity, low loss, and highly tunable ferroelectric elements. Relatively low loss factors, high dielectric breakdown strengths and easy mechanical treatment make ferroelectrics promising active elements for high power microwave tuning and switching devices. The main requirement for the electrical properties of ceramic materials to be used in such devices is a combination of the optimal value of the dielectric constant (ε=100-150), a high level of electric field tunability *K*=6-8% at 15 kV/cm bias field in air and relatively low dielectric losses in the 1300 MHz range.

The new technology with the use of specific annealing has demonstrated a dramatic reduction in relaxation processes in the dielectric response of the nonlinear material that allowed us to establish a direct correspondence between the bias field magnitude and the permittivity of the ferroelectric tuning element. In addition, the same technology provided an improvement in the loss factor of the active tuning element by a factor of ~ 2 in the L-band frequency range.

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