EXPERIMENTAL DEMONSTRATION OF AN X-BAND TUNABLE DIELECTRIC ACCELERATING STRUCTURE

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Abstract

The principal goals of the work described in this paper are a proof of nonlinear tunable ferroelectric material concepts for linear accelerator applications and the experimental demonstration of a tunable *dielectric loaded accelerating (*DLA) structure . Recently, a proposed method to adjust the resonant frequency of a **DLA** structure with a thick ceramic layer backed by a thin layer of ferroelectric has been studied experimentally. The overall frequency of the DLA structure was tuned by applying a DC bias voltage to the ferroelectric layer in order to vary its permittivity. We designed and tested a prototype planar 11.424 GHz double layer ferroelectric-ceramic structure consisting of a linear ceramic substrate (dielectric constant of (20 - 100), loss factor of $(2 - 4)\times10^{-4}$ and a BST-MgO composition ferroelectric substrate, dielectric constant of 400 - 500, loss tangent tan $\delta = (4 - 5)\times10^{-3}$ at X-band and tunability of 1.2-1.3 at 4-5 V/μm bias field. The frequency shift of a one-sided tunable DLA of 120-160 MHz has been demonstrated, leading to a predicted overall DLA structure frequency tuning range of (250 – 300) MHz.

INTRODUCTION

Dielectric loaded accelerator (DLA) structures excited by a high current electron beam or by an external high frequency high power RF source have been under extensive study in recent years [1]. The basic RF structure is very simple - a cylindrical, dielectric loaded waveguide with an axial vacuum channel is inserted into a conductive sleeve. In wakefield acceleration, a high charge, (typically 20 – 40 nC), short, (1 – 4 mm) electron drive beam generates TM01 mode electromagnetic Cherenkov radiation (wakefields) while propagating down the vacuum channel. This DLA structure can be excited by an external RF power source as well [1].

If developed, a *tunable* DLA will allow one to adjust the phase velocity of the DLA after it has been assembled into its final form. The need for frequency tuning (or phase velocity adjustment) of any accelerating structure arises from the fact that the phase velocity of the assembled accelerating structure will, in general, differ from the design phase velocity due to various sources of error. In a DLA structure, these errors can be caused by machining tolerance of the dielectric dimensions, thermal expansion of the structure, dielectric constant heterogeneity, etc. In summary, the feasibility of making DLA structures practical is greatly advanced by the development of a frequency tuning method. This new frequency adjustment technique has straightforward applications to the design of externally powered DLA structures, multistaging dielectric based accelerators, wakefield bunch train generation and two-beam acceleration schemes.

It is worth noting that low frequency accelerating cavities have in the past incorporated frequency tuning based on biased ferrites to adjust the effective cavity volume. The work proposed here differs in key respects: it represents the use of a ferroelectric-based technique [2] at Ka-band and X-band frequencies and is integral to the dielectric loaded structure.

FREQUENCY TUNING OF THE DLA STRUCTURE

The frequency spectrum of a conventional metallic accelerating structure is defined by the geometry of the waveguide. In addition to geometry, the frequency spectrum of a DLA structure is also affected by the ceramic loading inside the conducting walls. It was shown that the dispersion curves of dielectric waveguides are very sensitive to geometric factors [2]. We also point out that the dielectric constant homogeneity along the waveguide has technological limitations intrinsic to the manufacturing techniques used for the ceramic tubes e.g. particle size dispersion and firing temperature variations inside the furnace. Thus, without a method of tuning, the DLA structure would require a tight machining tolerance of the waveguide geometry and extremely expensive ceramic material manufacturing processes.

We propose to use a combination of ferroelectric and ceramic layers to permit tuning of a composite ceramic–ferroelectric waveguide while keeping the overall material loss factor in the $(4\div5)\times10^{-4}$ range [2]. It was shown that the losses in our composite structure are comparable to the losses in conventional DLA structures that consist of a single dielectric cylinder inserted into a conductive copper jacket [2].

The most notable feature of the tunable DLA is the replacement of a single ceramic by a composite of two layers. The inner layer is a linear ceramic, with permittivity ε_1, typically in the range of $4 \div 36$. The outer layer is a thin film made of BST ferroelectric, of permittivity ε_2, placed between the ceramic layer and the

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copper sleeve. Tuning is achieved by varying the permittivity, ε_2, of the ferroelectric film by applying an external DC electric field across the ferroelectric. This allows us to control the effective dielectric constant of the composite system and therefore, to control of the structure frequency during operation.

The ferroelectric layer is actually about a tenth the thickness of the ceramic layer. For structures in the 10 GHz frequency range the typical thicknesses are (2-3) mm for the ceramic layer and (200-300) µm for the ferroelectric film. It should be mentioned that this geometric ratio of 10 plays an important role for this structure design. The relative permittivity of the BST ferroelectric is typically in the range of 1000-2000. One can reduce this to 300-500 by using a mixture of BST and oxides to avoid any extra magnetic losses at the conducting walls [3]. A DC field can vary the permittivity of the BST-oxide material over the range of (20-30) % or about 100 units. Adjustment of the permittivity of the ferroelectric outer layer permits adjustment of the phase velocity of the structure. The loss factor of this composite DLA structure will be about the same as the ceramic-only structure due to the geometric ratio, since the volume of high loss ferroelectric material is much smaller than the basic ceramic.

EXPERIMENT

We recently fabricated and experimentally tested BST ferroelectric samples which, when a dc electric field is applied, allow varying of the effective dielectric constant of the rf resonator/waveguide loading material 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 at X-band and Ka-band as well as to define the tunability range of the newly developed nonlinear ceramic [4]. We also designed and tested a prototype planar 11.424 GHz double layer ferroelectric-ceramic structure consisting of a linear ceramic substrate (dielectric constant of (20 - 100), loss factor of $(2 - 4)\times10^{-4}$ and a BSM composition ferroelectric substrate of 0.5-1.0 mm thickness, dielectric constant of 400 - 500, loss tangent $\tan\delta = (4 - 5)\times10^{-3}$ at X-band and tunability of 1.2-1.3 at a 4-5 V/µm bias field. Using a one-sided (single layer of ceramic and ferroelectric) test structure, a frequency shift of 120-160 MHz has been demonstrated. This result implies a predicted overall DLA structure frequency tuning range of (250 - 300) MHz (2.5 - 3) %.

Material

We studied the nonlinear dielectric properties of the newly developed bulk BST-MgO (BSM) composite ferroelectric material [3]. We measured the dielectric constant ε, loss factor $\tan\delta$, tunability $\Delta\varepsilon/\varepsilon$ and the temperature dependence of the BSM composition at 1 MHz, 3-8 GHz, and at X-band and Ka-band as well. It was found that the dielectric permittivity of the BSM composition did not exceed 500, the loss factor was $(4\text{-}6)\times10^{-3}$ at X-band and $(6\text{-}8)\times10^{-3}$ at Ka-band, and the tunability range was 1.22-1.29 at 3.8- 4.5 V/µm dc bias field.

Special attention was paid to short dc voltage pulse measurements. The set of the BSM samples were tested with a pulse rise time of 10 µsec with a front edge of a few ns. The BSM samples demonstrated 5.8-7.5% tunability at 2 V/µ m bias field magnitude, corresponding to 15-24 % tunability at 4.5 V/µ m bias voltages for the short dc pulses applied. BSM ferroelectric substrates with dimensions $22.8\times25.0\times(0.5\text{-}1.0)$ mm^3 have been developed for an X-band tunable reflective resonator design. We also fabricated and tested a thin 200 µm substrate of 7.2×3.4 mm^2 surface area for Ka-band accelerator applications.

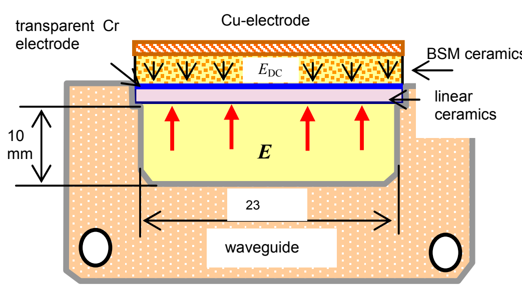

Figure 1: The cross-section of the resonator with a "transparent dc contact" design. Note the deposited 20-50 nm thick Cr contact on the lower surface of the ferroelectric substrate.

Temperature dependence of the BSM ferroelectric parameters.

The permittivity variation with temperature of the BST-MgO (BSM) ferroelectric substrates has been studied. We measured the dielectric permittivity at 70-310 ^{0}K at 1 MHz and at 280-310 ^{0}K at Ka band frequencies. The dielectric constant variation with temperature has been determined to be in the range $\Delta\varepsilon/\Delta T$=3.12-3.30 /^{0}K.

The temperature rise of a typical dielectric loaded accelerating structure operating at X-band at 10-50 MW input power, 500 ns pulse duration and 1-10-100 pps rep-rates has been studied [5]. It was found that at the power levels used and 1-10 pps rep-rate the temperature rise is insufficient to affect the dielectric constant. We have designed planar and cylindrical structures numerically that are able to operate reliably at 100 pps rep rate. A key feature of our new design is a thermoconductive AlN ceramic layer between the ferroelectric and the copper sleeve. This ceramic will provide both heat extraction and reduction in wall losses for the structure.

Design of the Double-Layer Tunable Structure.

Adjusting the permittivity of the ferroelectric requires the use of a DC bias field. The electrode geometry used to produce the bias field must be compatible with the rf accelerating mode of the structure. The "transparent electrode" technology was developed to improve the overall tunability of the 11.424 GHz dielectric loaded accelerating structure. It allowed us to overcome the high voltage biasing limitations of the inter-digital bias electrode topology that had been used previously for tunability measurements of ceramic substrates [4]. We deposited a thin layer (20-50 nm) of Cr on the surface of the ferroelectric substrate on the side facing the linear ceramic. The biasing field is produced by applying HVDC between the Cr layer and the grounded resonator wall (**Fig.1**). The contact is completely transparent to the microwave fields, as the metal thickness of 20-50 nm is much less than the skin depth in Cr at 10 GHz,. The outer surface of the ferroelectric is metallized with a copper layer held at ground potential.

The transparent electrode technology presented here enables higher biasing voltages to be applied to the ferroelectric substrate as well as providing the required degree of dc field homogeneity inside the BSM substrate.
We plan to use R. Konecny's design of a Super High Vacuum dc adapter based on a commercial 20 kV dc connector for supplying the dc bias voltage to the operational dielectric accelerating structure.

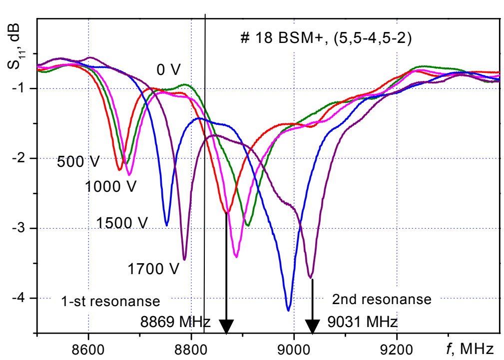

Figure 2: S11 parameters of the X band "transparent contact" resonator. BSM substrate 23×19×1.0 mm^3, permittivity of the ceramic and ferroelectric of 20 and 481 respectively, frequency shift of 116 MHz (first resonance) and 162 MHz (second resonance) at a 1.7 V/µm bias field.

Tunable DLA Structure Demonstration.

We experimentally studied the tunability of the BSM ferroelectric substrate over the 9 – 12 GHz frequency range. The tunability factor and overall resonator frequency shift for BSM ceramics has been studied using a tunable rectangular resonator partially filled with ceramic and ferroelectric layers. We fabricated the tunable resonator as a section of standard rectangular waveguide (22.8 × 10) mm^2. The polarization of the feeder waveguide provides the orthogonal polarization of the TE_{01} mode. We used two different linear ceramics, one with dielectric constant ε = 10-20 and thickness of 1.0 mm, the other with permittivity 100 and thickness of 0.5 mm. The outer layer was a ferroelectric BST-MgO (BSM) ceramic substrate either 1.0 mm or 0.5 mm thick. The total ceramic layer thickness did not exceed of 1.5 mm.

The best result was obtained using a BSM ferroelectric sample [3]**.** The resonance curves (S11 of the test cavity) of this experiment are shown in **Fig. 2**. The first resonance displacement did not exceed 116 MHz at 1700 V, but we achieved the largest peak shift of 162 MHz for the second resonance line at the comparatively low dc field of 1.7 V/µm**.** The overall frequency shift of the X-band prototype tunable accelerating structure has been demonstrated in the range of 100-160 MHz at (1.7-2.5) V/µm applied dc bias field, corresponding to a 250-300 MHz tuning frequency range for a double-sided planar dielectric loaded accelerating structure.

SUMMARY

A new scheme for tuning DLA accelerating structures is presented. Adjusting the permittivity of the ferroelectric requires the use of a DC bias field. The transparent electrode technology was developed to improve the overall tunability of the 11.424 GHz tunable dielectric loaded accelerating structure. The transparent electrode technology presented here enables higher biasing voltage to be applied to the ferroelectric substrate as well as providing the required degree of dc field homogeneity inside the BSM substrate. The frequency shift of the one-sided tunable DLA of 120-160 MHz has been demonstrated leading to an overall DLA structure frequency tuning range of (250 - 300) MHz.

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