A METHOD FOR TUNING DIELECTRIC LOADED ACCELERATING STRUCTURES

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Abstract

We present a method to vary the resonant frequency of a *dielectric loaded accelerating* (**DLA)** structure driven by either the wakefield of a beam or an external rf source. The structure consists of a thick ceramic layer backed by a thin layer of ferroelectric. The overall frequency of the DLA structure is tuned by applying a DC bias voltage to the ferroelectric layer in order to vary its permittivity. This scheme is needed to compensate for frequency shifts in DLA structures due to machining imperfections and dielectric constant heterogeneity. We have identified BST ferroelectric-oxides compounds as a suitable material for this application; it has a relative dielectric constant that can be tuned from 300 to 500. From this, we calculate that the overall frequency of the structure can be tuned over a range of (2÷4)% for an X-band DLA structure. In this paper, a detailed model of the DLA structure is given and an experimental test is proposed. We present cold test measurements for an 11.424 GHz planar tunable DLA structure.

INTRODUCTION

Frequency control of any accelerating structure is a fundamental issue. Synchronization between the electron beam velocity and the phase velocity of the accelerating field must be maintained in order for the bunch to gain energy. A frequency error in the accelerating structure will result in a change in the phase velocity of the accelerating field and thus a loss of synchronization between the beam and field. Lack of frequency control also causes problems for multistage accelerators where one has to match the accelerating field frequencies between adjoined sections. One can see that the capability of tuning the accelerating structure is a basic necessity for acceleration.

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. For example, if we design it for 11.424 GHz, choose a ceramic material with the dielectric constant of 16, and an inner radius of 5mm, then the outer radius is 6.647 mm. For this particular structure, the phase velocity of the accelerating mode will be mismatched to the electron beam speed by 7.03% if the outer radius of the structure increases by 0.1%, or 6.7 μm. One can see that the dispersion curves of the waveguides are very sensitive to the geometry. We also point out here that the dielectric constant homogeneity along the waveguide has technological limitations due to the manufacturing techniques used for the ceramic tubes e.g. particle size dispersion and firing temperature variation inside the furnace. Thus, the DLA structure requires a method of tuning to avoid an overly stringent machining tolerances and expensive ceramic material manufacturing processes.

BASIC CONCEPTS: HOW TO VARY THE PERMITTIVITY.

There are two classes of materials that can be tuned, in other words, materials with electromagnetic properties that can be controlled by external fields: **ferrites**, controlled by magnetic fields, and **ferroelectrics**, controlled by electric fields. Ferrite material does not appear to be a practical solution for high frequency, high gradient accelerators because of its extremely high loss factor and also because the magnetic field will interfere with the electron beam optics. The use of ferroelectrics for tuning purposes would appear to be a natural solution, except for the fact that ferroelectrics are very lossy in the > 10 GHz frequency range. The typical loss factor for $Ba_xSr_{1-x}TiO_3$ (BST) ferroelectric, commonly used at room temperature, is $(1\div3)\times10^{-2}$ near 10 GHz frequency range. However, a new scheme involving ferroelectrics [1,2] allows control of the dielectric constant (and consequently the frequency spectrum) for the dielectric waveguides by incorporating ferroelectric layers., while simultaneously having low loss. For example, the loss factor for a good linear microwave ceramic is $(0.5\div5)\times10^{-4}$.

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. It will be 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.

The most notable feature of the tunable DLA is the replacement of a single ceramic by a composite of 2 layers as shown in Fig. 1. The inner layer is ceramic, with permittivity ε_1, typically in the range of 4÷36. The outer layer is a thin film made of BST ferroelectric, of permittivity ε_2, placed between the ceramic layer and the copper sleeve. The DLA structure 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

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dielectric constant of the composite system and therefore, to control of the structure frequency during operation.

The basic design of the cylindrical geometry is shown in Fig. 2. The relative depths of the layers in this figure are not to scale; the ferroelectric layer is actually 10 times thinner than the ceramic layer.

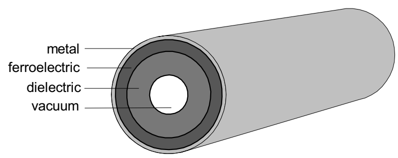

Figure 1. Basic designs of tunable dielectric accelerating structures, cylindrical geometry, outer layer is ferroelectric, inner layer is ceramic.

The typical thickness is (2÷3) mm for the ceramic layer and (200÷300) μm for ferroelectric film. It should be mentioned that this geometric ratio of 10 plays an important role for this structure design. The dielectric constant of the BST ferroelectric is typically within 1000÷2000, and we have reduced this by using a composition of BST and oxides to 300÷500 to avoid any extra magnetic loss at the conducting walls. A DC field can vary this dielectric constant in the range of (20÷30)% or about 100 units. Thus the primary ceramic layer with the dielectric constant of (4÷20) and (2÷3) mm in thickness, will be tuned by the comparatively thin (200÷300) μm ferroelectric layer. 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 that of the basic ceramic.

Numerical Simulations

We have simulated the radial dependence of the electric field components for the 11.424 GHz dielectric loaded cylindrical waveguide with the ferroelectric layer of 200 μm and dielectric constant of 500 excited by the high current beam of 100 nC, $\sigma_z = 2$ mm. The accelerating gradient of 30 MV/m is flat inside the vacuum channel and decays rapidly inside the ceramic layer. The ferroelectric tunability depends on the ratio between the DC and RF axial field magnitudes. The DC field inside the ferroelectric layer does not exceed 10 V/μ. Our simulations show that the maximum longitudinal RF field inside the ferroelectric layer for the 11.424 GHz structure is $E_z = 0.23$ MV/m and therefore $Ez_{vacuum}:Ez_{ferro} = 166$ and $E_{DC}:Ez_{ferro} = 43.5$. These ratios mean that the ferroelectric layer remains tunable since the effect of the beam and RF field is negligible in comparison with the DC field between the microstrip contacts. It should be mentioned that transverse field magnitude is much less than the longitudinal inside the ferroelectric as well, $Ez_{ferro} >> Er_{ferro}$.

Microstrips

One has to supply a dc field into the ferroelectric layer to vary the dielectric constant of the structure loading. We have developed a technique to deposit copper microstrip (using a photolithography) on substrate samples in order to measure the tunability and loss tangent of an 11.424 GHz planar structure. The microstrip geometry configuration used for supplying the bias field to the ferroelectric layer also suppresses the transverse dipole wakefield suppression. This is discussed in [A. Kanareykin et al, TPPG041, these Proceedings].

FERROELECTRIC PROPERTIES

A promising principle to tune microwave devices is the use of the nonlinearity of a ferroelectric material. A ferroelectric crystal or ceramic is a material with a spontaneous dielectric polarization below a Curie temperature T_c. A representative ferroelectric material is a $BaTiO_3$ - $SrTiO_3$ solid solution (BST). Above T_c, the ferroelectric is in a paraelectric phase and does not show spontaneous polarization, but still has the dielectric nonlinearity. The BST solid solution can be synthesized in the form of a polycrystalline or ceramic layer on the dielectric substrate.

As stated above, we seek a DLA structure design for the frequency range f = (10÷13) GHz with a tunability of (2÷3)% or ~ 200 MHz. In this section, we describe the properties of our BST ferroelectric and present cold test results of the 11.42 planar GHz DLA structure.

Ferroelectric Composition

The ferroelectric properties we need to produce for the DLA structure are: (1) dielectric constant in the range of 200÷800; and (2) loss tangent of $(1÷6)\times10^{-3}$ at the 10÷13 GHz frequency range. Available materials are made of a BST matrix with oxides doping. For room temperature applications the $Ba_xSr_{1-x}TiO3$ (BST) ferroelectric is typically made with x < 0.7. Normally, BST thin films for high frequency applications have Ba:Sr ratio of 50:50 or 60:40. For our application we require a bulk ferroelectric material or thick film ferroelectric on a ceramic substrate.

Loss Factor

A typical loss factor for a thin (1μ) ferroelectric film is ~ $(1÷5)\times10^{-2}$ for the 10 GHz band [2]. Recently, we have obtained an encouraging result that showed the loss factor of 4×10^{-3} at 35 GHz for the dielectric constant of 495 and DC field variation from 2.8 V/μm to zero [3,4]. The expected loss factor for our BST-oxides composition is $(2÷5)\times10^{-3}$ for the 11 GHz frequency range.

We have chosen the tunability of the structure not to exceed 3% to allow us to adjust for a maximum 200 MHz frequency shift. The 11.42 GHz cylindrical structure (Fig. 1) parameters are: vacuum channel radius of 0.5 cm, dielectric radius of 0.633 cm, ferroelectric layer thickness of 230 μ, dielectric constants of ceramic and ferroelectric are 16 and 250 respectively. Lines 3 and 4 show ratios between the wall and ferroelectric losses, and line 5 shows the ratio of the loss factor of the 11.42 GHz tunable structure and equivalent DLA (no extra layer) structure designed for the same 11.42 GHz frequency [2].

Table 1. The 11.424 GHz tunable DLA structure loss factor ratios. Tunability factor is of 2.22%.

1	Thickness of ferroelectric	230 μ
2	Loss factor of ferroelectric	5×10^{-3}
3	Ferroelectric losses,%	26.6
4	Wall losses, %	63.9
5	Loss ratio	1.632

It should be noticed that we have to take into account the increase in the losses of the conducting walls if we use the tuning ferroelectric between the ceramic layer and the metal. However, the total ratio of losses in the tunable structure to the same frequency structure made only with ceramic is in the range of (1.7÷1.8), $W_{diel}/W_{ferr} < 2$. (line 5 of the table, "Loss ratio"). It means that our price for tunability is the increase of energy loss by (1.5÷2.0) dB for the double layer 3% tunable accelerating structure in comparison with a (non-tunable) dielectric loaded waveguide.

Planar Tunable DLA Structure Demonstration

A BST ferroelectric doped with the oxides composition, with loss factor of 4×10^{-3}, and dielectric constant of 500 has been synthesized [3,4]. Tunability measurements of the ferroelectric developed have been done at 9÷11 GHz by the cavity "open wall" resonator method. The basic idea is shown in Fig. 2: in the wall of the waveguide of the required frequency we cut out windows on opposite sides. We made a "landing" place of 20×30 mm into the waveguide wall for the testing substrates. A set of 2 substrates has been used for this demonstration: (1) a ceramic inner substrate, with the dielectric constant of 100 and thickness of 2 mm; and (2) a ferroelectric outer layer of 500 μm and dielectric constant of 495. We used a photolithography deposition to put the microstrip contacts onto the substrate surface. The negative group was grounded and the positive group was connected to a high voltage DC power supply. The best result we achieved, using an electric field of 1400 V DC, corresponds to 2.8 V/μm dc field applied to the ferroelectric sample. We measured a **106 MHz** shift, or 1.1% at 9.5 GHz with the ferroelectric material tunability factor of 9.5%. Recently, we have fabricated the samples with a tunability factor of 15% for the same biasing field of 2.8 V/μ. We did not observe any sign of saturation and we expect a tunability factor in the range of (22÷25)% for the new samples tuned by the bias filed of 5 V/μm. The overall planar structure tunability factor will be in the range of **(2.1÷2.4)%** that corresponds to **228 MHz** frequency shift.

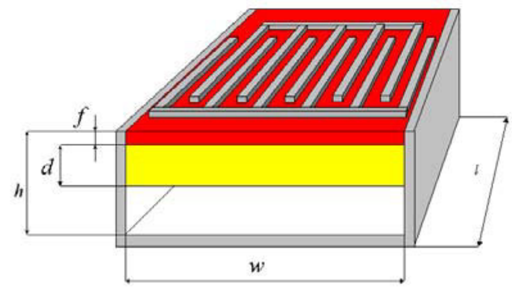

Figure 2. Tunable planar 11.424 GHz structure with open walls. One can see the ferroelectric substrate with the microstrip contacts (interdigital configuration) to supply bias voltage into the ferroelectric material.

SUMMARY

A new scheme for the tuning of DLA accelerating structures is proposed. The basic idea is to use a double layer of dielectric. The outer layer, made of ferroelectric material with permittivity controlled by an applied DC field, will tune the whole accelerating structure to the desired frequency. The (9÷11) GHz tunable DLA structure has been tested with a ferroelectric layer 500 μ thick with a dielectric constant of 495, tunability of 9.5%,a loss factor of 4×10^{-3}, and a peak applied DC bias field of 2.8 V/μ. The overall structure tunability of **1.1%** or **106 MHz** was demonstrated. This tuning effect is fast and programmable in real time (< 1 μsec) during operation of the accelerator.

The multi-layer tunable technology can also be extended to many other high frequency, high power devices.

This work is supported by the US Department of Energy, grant SBIR DE-FG02-02ER83418. The ferroelectric samples have been fabricated for the Omega-P, Inc. project [V.P. Yakovlev et al, TPAE031, these Proceedings], the project that initiated the research of our ferroelectric group under support to Omega-P, Inc. through DoE SBIR Phase I grant DE-FG02-02ER83537.

REFERENCES

[1]. A. Kanareykin, I. Sheinman, A. Altmark, Technical Physics Letters, Vol. 28, N. 11, pp. 916-918, 2002.

[2]. A. Kanareykin, W. Gai, J. Power, A. Altmark and I. Sheinman, AIP Conference Proceedings, N 647, pp. 565-575, 2002.

[3]. E. Nenasheva, A. Kanareykin, N. Kartenko, S. Karmanenko, International Conference on Electroceramics, MIT, Cambridge, MA, USA, 2003. (To be published).

[4]. S. Karmanenko, A. Kanareykin, E. Nenasheva, A. Dedyk, A. Semenov, The 10th European Meeting on Ferroelectricity. Cambridge, UK, 2003. (To be published).