A DOUBLE-LAYERED, PLANAR DIELECTRIC LOADED ACCELERATING STRUCTURE

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Abstract

Recently, a method to tune *dielectric-loaded accelerating (DLA)* structures has been proposed [these proceedings]. In these structures, a ferroelectric layer backs a conventional ceramic layer, thus allowing the effective dielectric constant of the waveguide to be varied by applying a DC electric field to the ferroelectric layer. In this paper, we present a design for a planar version of this double-layered, tuneable DLA structure. The advantage of the planar waveguide is its spectral uniformity, ease of frequency tuning, and its simplicity of fabrication. The dispersion equation for the structure and the accelerating wakefield exited by a planar electron bunch has been calculated. Based on this work, we present simulation results for 13, 20 and 35 GHz structure parameters including tunability factor. The transverse deflecting wakefields caused by the beam offset have been studied as well. In addition, we present the results of cold test measurements for an 11.4 GHz, double-layered, ceramic-ferroelectric test device, including tuning range and Q measurements.

INTRODUCTION

The field of advanced accelerators is in search of novel revolutionary technologies to allow progress in particle accelerators for high-energy physics experiments. Techniques based on the Dielectric Wakefield Accelerator (DWFA) [1] concept are some of the most promising to date in terms of their potential to provide high gradient accelerating structures for future generation linear colliders. These structures may be excited by a high current electron beam or an external high frequency high power RF source and have been under intensive 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. A high charge, (typically 20÷40 nC), short, (1÷4 mm) electron *drive* beam generates TM_{01} mode electromagnetic Cherenkov radiation (wakefields) which, propagating through the waveguide vacuum channel, is used to accelerate a less intense beam pulse following at an appropriate distance.

The planar accelerating structures can produce a high accelerating gradient and can easily be fabricated. It is desirable to operate accelerating structures at high frequencies to overcome breakdown limits of the structure. Simply scaling cylindrical geometry to low wavelengths limits the accelerator luminosity. It should be noticed that high frequency dielectric structures also require tight mechanical tolerances and their fabrication becomes difficult. In [2], the slab type of dielectric structure has been studied using a normal mode analysis. Previously, the planar boundless structures have been studied in [3] and the structure excitation by the short beam were presented in [4] a rectangular dielectric-lined structure having micron-scale dimensions presented in [5] Experimental demonstration of the high frequency planar structure has been done in [6]. Recently, a method for tuning the DLA structures has been proposed [7]. The ceramic loading covered by the relatively thin ferroelectric film allows for tuning the entire structure due to the dielectric material nonlinearity. In this paper, we present a planar *tunable dielectric loaded accelerator* mode analysis, design, and cold test results.

TUNABLE PLANAR DLA STRUCTURE

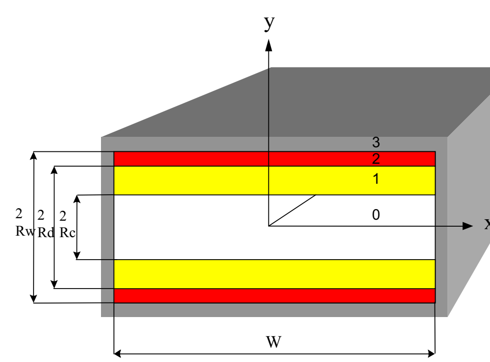

Figure 1. Double-layer Tunable Planar DLA structure. Inner layer is a ceramic substrate, the outer one is made of BST ferroelectric.

DLA structures, in comparison with vacuum ones, have an important parameter that determines the frequency spectrum - the dielectric constant of the loading material. In [7] a new scheme was proposed allowing control of the dielectric constant (and consequently the frequency spectrum) for the dielectric waveguides by incorporating ferroelectric layers. The most notable feature of the tunable DLA is the replacement of a single ceramic by a composite of 2 layers. The outer layer is a film made of BST ferroelectric placed between the ceramic layer and the copper wall. The DLA structure tuning is achieved by varying the ferroelectric permittivity by applying an external DC electric field across the ferroelectric. The design shown in Fig. 1 is not the only one possible; the positions of the layers can be swapped so that the ferroelectric film will form the inner layer. The advantage of this configuration would be the reduction of the magnetic loss on the conducting copper walls, while the disadvantages would be high gradient RF fields on the ferroelectric material surface, scattered electrons and increased heating. We consider the outer layer is a

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ferroelectric one, dielectric constant of 500, loss factor of 4×10^{-3} at 11.424 GHz, the inner layer is made of ceramic, dielectric constant of 20÷30, loss factor of $(1\div3)\times10^{-4}$. The normal modes in dielectric loaded guides are LSM and LSE modes that have no H or E components normal to the dielectric/ ferroelectric interface. In each slab, the fields for LSM/LSE modes were derived from the electric/magnetic Hertz potential and satisfied the boundary conditions at the interface between ferroelectric/dielectric and dielectric/vacuum.

The electron beam passes the vacuum channel along an axis waveguide with an initial offset. The wakefield is generated behind the bunch if the dielectric material satisfies the Cherenkov radiation terms:

$V = \beta c$ and $\beta > \varepsilon^{-1/2}$.

Solving the equations for E_z and H_z, substituting them to boundary conditions and equating zero determinants of the turned out systems, one can obtain the dispersive equations for antisymmetric and symmetric solutions corresponding to:

$$\Delta_{\text{odd}}(k, k_x) = 0, \; \Delta_{\text{even}}(k, k_x) = 0, \quad (1)$$

where $k_x = 2n\pi/w$ for antisymmetric solutions and $k_x = (2n+1)\pi/w$ for symmetric ones.

The expressions for longitudinal components of electric and magnetic fields E_z and H_z can be written as:

$$E_z(x,y,\zeta) = \sum_{n,m=0}^{\infty} E_{z\,m,n_p}(x,y,k_{n,m})\cos(k_{z\,n,m}\zeta), \quad (2)$$

$$H_z(x,y,\zeta) = \sum_{n,m=0}^{\infty} H_{z\,m,n}(x,y,k_{n,m})\cos(k_{z\,n,m}\zeta), \quad (3)$$

where $k_{n,m}$ are roots of the dispersive equations (1), $\zeta = z - Vt$, $E_{z\,m,n}(x,y,k_{n,m})$ and $H_{z\,m,n}(x,y,k_{n,m})$ are defined by the boundary conditions. Other field components of electrical and magnetic fields can be written through E_z and H_z.

The Planar DLA Structure Parameters

Table 1. Tunable rectangular waveguide parameters.

№	w, cm	R_c, cm	d, μm	R_w, cm	ε_1	ε_2	$\delta\varepsilon_2$	f, GHz	δf %
1	4	0.5	150	0.6048	16	500	25%	13.625	2.0
2	4	0.5	90	0.5639	16	500	25%	20	2.2
3	4	0.3	55	0.3355	16	500	25%	35	2.9

Table 1 shows the Tunable DLA structure parameters corresponding to planar geometry presented in Fig. 1. for the 13, 20 and 35 GHz frequency range. The ferroelectric layer thickness of d decreases for the high frequencies, $\delta\varepsilon_2$ is the dielectric permittivity variation of the ferroelectric layer, $\delta\varepsilon_2 = \Delta\varepsilon/\varepsilon$. One can see the ferroelectric dielectric constant variation within 25% causes $\delta f = (2\div2.9)\%$ overall frequency adjustment of the planar DLA structure.

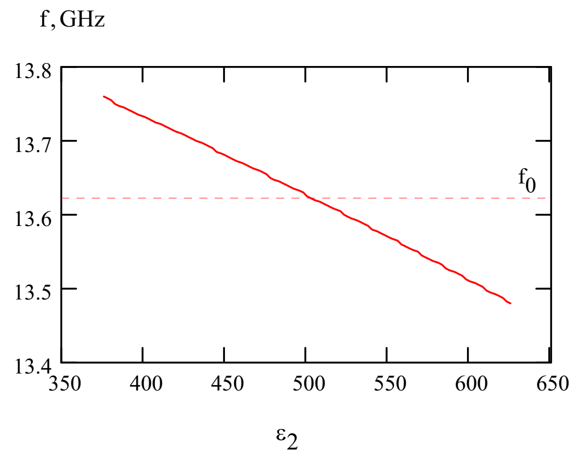

Figure 2. 13.625 GHz frequency variation vs. dielectric constant of the ferroelectric layer. The waveguide parameters correspond to line 1 of Table 1.

Fig. 2 shows the 13.625 GHz structure frequency shift caused by the dielectric constant variation of the ferroelectric layer, tunability factor of the ferroelectric material was of 20÷25%.

Wakefields

In Table 2, the parameters of the electron beams that will be used in the planning experiments are presented. The first line of the table corresponds to the beam passing the structure almost along the central axis, offset is 0.03 cm. The beam is misalignment at line 2, the offset is 0.5 cm off the x and 0.2 cm off the y respectively.

Table 2. Electron bunch parameters.

№	q, nC	W, MeV	x_0, cm	σ_x, cm	y_0, cm	σ_y, cm	z_0, cm	σ_z, cm
1	100	150	0.03	0.49	0.03	0.12	0	0.4
2	100	150	0.5	0.375	0.2	0.075	0	0.4

Accelerating longitudinal gradient is shown in Figure 3, peak magnitude is 22 MV/m. It should be noticed that the similar cylindrical (11÷13) GHz accelerating structure supports the single mode wakefields for the 0.4 cm long bunches [7] At the same time, wakefields excited by the 0.4 cm long bunch passing through the 13 GHz planar structure show multimode properties of the structure, Fig.3.

Fig. 4 and 5 present a 3D picture of the wakefields, Fig. 4 corresponds to the beam position slightly deflected off the z ax, line of Table 2, the accelerating gradient is flat at the cross section of the structure. Fig. 5 present the worse case where the beam is deflected, line 2 of Table 2, the peak gradient is deflected as well. The magnetic field H_z magnitude increases near the wall boundary as expected due to the high value of the ferroelectric dielectric constant, thus one can predict significant wall losses for this kind of structure.

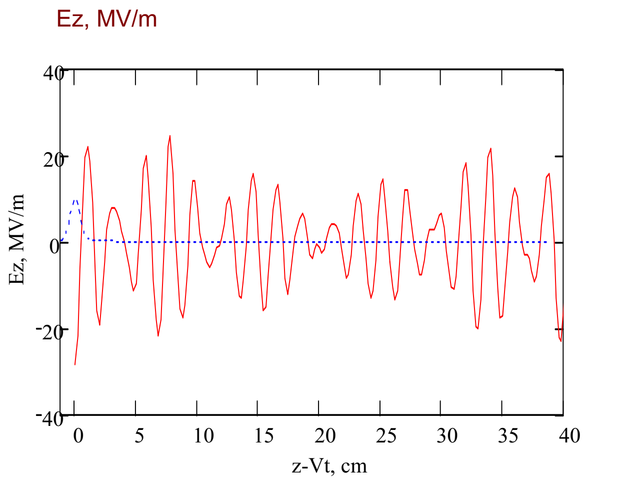

Figure 3. Accelerating field E_z vs. the distance behind the bunch $\zeta = z - Vt$ excited by the 100 nC beam. Beam parameters are presented in Table 2, line 1.

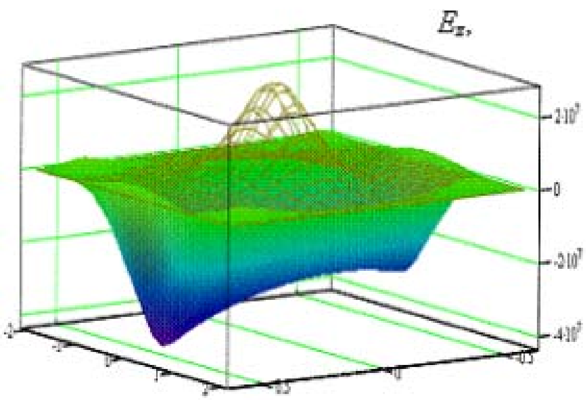

Figure 4. Longitudinal accelerating gradient at the cross section of the planar DLA structure. Beam parameters are presented in Table 2, line 1.

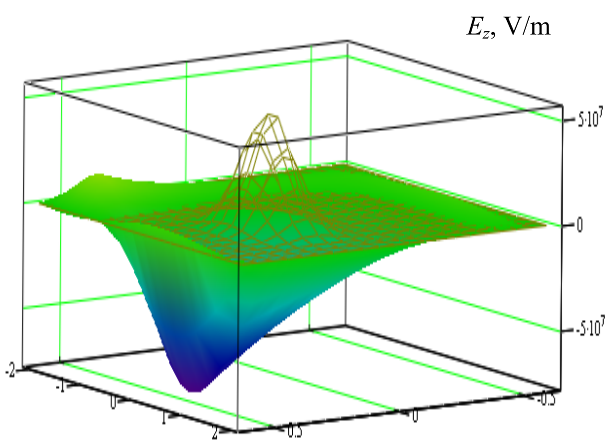

Figure 5. Longitudinal accelerating gradient at the cross section of the planar DLA structure. Beam parameters presented in Table 2, line 2. The beam is misaligned and the peak gradient is deflected as well.

Cold Test Measurements

Tunability measurements have been done at 9.5 GHz by cavity "open wall" resonator [8] Dielectric constant of the ceramic substrate was 100. Electric field of 1400V applied to BST sample (dielectric constant of 495) that corresponds to 2,8 V/μ bias field. We measured the 106 MHz frequency shift, tunability factor of the material was 9.5%.

SUMMARY

A planar tunable dielectric loaded accelerating structure was presented and the frequency tunability factor was calculated. Accelerating gradient dependence on the beam misalignment was studied and the cold measurement results were presented.

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