34.272 GHZ MULTILAYERED DIELECTRIC-LOADED ACCELERATING STRUCTURE*

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Abstract

A multilayered 34.272 GHz dielectric accelerating structure is described that is based on the Bragg fiber concept. Alternating radial dielectric layers of permittivities 38 and 9.7 create multiple reflections to confine the accelerating fields, thus greatly reducing the power losses from the external metal wall. The structure will operate at TM_{03} mode instead of the usual TM_{01}. Numerical examples for 2- and 4-layer structures are presented with detailed analysis of TM (acceleration) modes. We found that the power attenuation of a 34.272 GHz dielectric loaded structure can be reduced from ~ 20 dB/m for a conventional single layer structure to less than 6 dB/m for a 2 or 4 layer structure. We also present a coupler design for the multilayered dielectric-loaded accelerating structure, which has the capability of mode selection and high efficiency RF transmission.

INTRODUCTION

Conventional Dielectric-Loaded Accelerating (DLA) structures have been demonstrated to have great potential as advanced accelerating devices in recent experimental studies [1, 2]. However, a major concern for this approach is the relatively high field attenuation per unit structure length caused by the strong magnetic fields (leading to high surface current) at the outer conducting wall. Particularly in the higher frequency ranges (millimeter wave), the large field losses will limit the utility of DLAs in high gradient accelerator applications. In our previous work [3] we proposed a new multilayered DLA structure design to reduce the RF power attenuation in the single layered DLA structure and at the same time to improve its shunt impedance.

The principal goal of this project is to develop a multilayer DLA, a dielectric structure consisting of concentric tubes with different dielectric constants. The structure proposed in this paper has a dramatically improved attenuation compared to a conventional single layer dielectric loaded structure while maintaining a comparable shunt impedance. These properties make the multilayer structure a good candidate for application in accelerators. In the multilayer DLA, the power attenuation is reduced using the Bragg fiber concept where the dielectric layers are used to create multiple reflections in order to confine the accelerating fields. The dielectric layers provide a number of boundaries that reduce the magnetic field magnitude at the copper jacket that forms the outer boundary of the structure. This allows a saving of the stored energy and decreases the overall DLA structure attenuation.

We have studied a 34.272 GHz cylindrical metallic waveguide lined with multiple layers of dielectric for use as a slow-wave microwave accelerating structure. Field solutions for *TM* (acceleration) modes and numerical examples for multilayered structures based on 2- and 4-layer designs are presented. A new mode-selective coupler is also discussed.

MULTILAYERED DLA STRUCTURE

Figure 1 gives the general configuration of a multilayered DLA structure. A vacuum channel of radius b_o, surrounded by alternating dielectric layers with two different dielectric constants is enclosed in a cylindrical metallic waveguide of radius b_N. For a given RF frequency, the radius b_i of each layer is determined by the synchronous condition (wave phase velocity equal to particle velocity, typically close to the speed of light) and dielectric constant ε_i. One can optimize the accelerator properties by varying the b_i and ε_i.

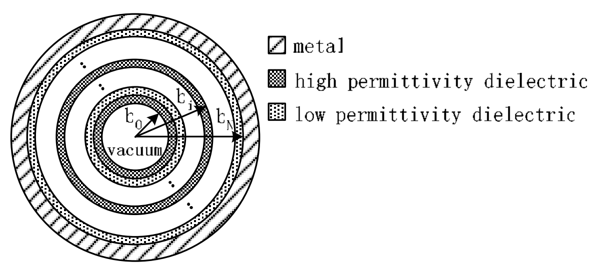

Figure 1: Cross-section of the general multilayered DLA structure.

Modes that are of primary interest for beam acceleration in the multilayered DLA structure are TM modes which have longitudinal electric fields to accelerate charged particles. The general EM field solutions of TM_{0n} modes for the i^{th} dielectric layer can be expressed by

$$E_{zi}(z,r,\phi) = [A_i J_m(k_i r) + B_i Y_m(k_i r)] e^{j(\omega t - \beta z)} \qquad (1)$$

where

$$k_i = \omega \sqrt{\frac{\mu_{ri}\varepsilon_{ri}}{c^2} - \frac{1}{{v_p}^2}} \qquad (2)$$

$$\beta^2 = \omega^2 \mu_0 \varepsilon_0 \mu_{ri} \varepsilon_{ri} - {k_i}^2$$

v_p is the phase velocity of the wave traveling inside the

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tube, c is speed of light in free space, and k_i is the cutoff wave number in the i[th] layer. The quantity β is the wave propagation constant. The z axis is assumed to be the propagation direction. μ_{ri} and ε_{ri} are respectively the relative permeability and permittivity for the i[th] layer. From Maxwell's equations the other four field components can be derived from equation (1) directly by using

$$E_{ri} = \frac{-j}{k_i^2}\beta\frac{\partial E_{zi}}{\partial r}$$
$$H_{\phi i} = \frac{-j}{k_i^2}\omega\varepsilon_i\frac{\partial E_{zi}}{\partial r} \quad (3)$$

In each layer, there are two unknown coefficients A_i and B_i. Applying boundary condition between successive layers and on the metal surface we can obtain a recurrence relation from the i[th] layer to the (i+1)[th] layer,

$$\begin{pmatrix} A_N \\ B_N \end{pmatrix} = M_{N-1}\cdots M_1 M_0 \begin{pmatrix} A_0 \\ 0 \end{pmatrix}$$
$$A_N J_m(k_N b_N) + B_N Y_m(k_N b_N) = 0 \quad (4)$$

where M_i, i=0, 1….N, is transfer matrix for the i[th] boundary shown in figure 1, and b_N is the radius of the inner surface of metal wall. The condition for existence of non-trivial solutions for equation (4) is equivalent to the dispersion relation for TM0n modes in this waveguide. The detailed solutions for other TE and HEM modes is found in [3].

34.272 GHz MULTILAYERED STRUCTURE

In principle, higher operating frequencies allow higher accelerating gradients to be achieved inside the accelerator, a key issue in the design of future linear accelerators. However, both the conventional metal accelerating structure and the dielectric loaded structure (single layered DLA structure) suffer from the problem of rising RF power losses at higher operating frequencies. The multilayered DLA structure provides an option to address this problem. In this section, we give an example of a Ka-band (34.272 GHz) multilayered DLA structure with 2 or 4 dielectric layers (*N=2 or 4*). We use the same optimization procedure shown in reference [3] to obtain minimum field attenuation. The mode launched in the 4-layer DLA structure is TM_{03} mode; for the 2-layer structure instead of the TM_{02} mode we also use the TM_{03} mode as the accelerating mode in order to obtain higher Q and comparable shunt impedance. The permittivity for the alternating ceramic layers is 38 and 9.7, and loss tangent is assumed to be 10^{-4} for both. Dimensions of the 4-layer DLA structure after the optimization procedure are b_0=3mm, b_1=3.71mm, b_2=4.51mm, b_3=4.88mm, b_4=5.67mm; while the two layer structure has b_0=3mm, b_1=3.71mm, b_2=6.05mm.

The first column in Table 1 summarizes the characteristic parameters of this structure. Note that the quality factor *Q* is computed including both copper wall and dielectric losses. These same parameters for a single-layer DLA structure that has a single dielectric layer with dielectric constant of 38, and dimensions of b_0=3mm, b_1=3.33mm are shown in the third column of Table 1. The TM_{01} mode is the accelerating mode. Comparison of the 4-layer and the single-layer structures shows that both shunt impedance *r* and power attenuation α_0 have been improved remarkably. Even though *r/Q* is smaller, due to a much higher Q, than that of the single-layer DLA structure, the 4-layer structure still has comparable performance by comparison with the all metal structure. The second column of Table 1 gives the accelerating parameters of a double layered DLA structure which balances the good performance of the 4-layer structure and the simple fabrication of single layer device.

Table 1: Accelerating mode RF parameter comparison for different DLA structures.

	4-layer DLA Structure	2-layer DLA Structure	Single-layer DLA Structure
Synchronized Freq. (GHz)	34.272	34.272	34.272
Group Velocity (×c)	0.083	0.09	0.13
Q	8549	6044	1075
r (MΩ/m)	20.9	12.1	7.16
r/Q (Ω/m)	2444	2003	6660
Power Attn α_0 (dB/m)	4.4	5.6	22.7

MULTILAYAER CERAMIC WAVEGUIDE DESIGN

Extremely high manufacturing tolerances are required for this structure. The alternating permittivity tubes must fit tightly together to form the dielectric loading. A new technology to produce 7-10 cm long ceramic waveguides of uniform dielectric constant and tolerances required for the multilayered dielectric accelerating structure experiment is discussed in this section.

Production of dielectric tubes with a diameter ~ 10 mm made of small grain powders demands the use of modern ceramic engineering methods for forming these tubes, particularly the use of isostatic pressing. This technology will ensure the homogeneous compression of the material along the total waveguide length to provide uniform dielectric properties of the ceramic tube. It will significantly decrease the probability of the appearance of macro defects in the bulk of the tube during sintering and will increase the uniformity of the waveguide electronic parameters.

A new technology of manufacturing double and 4 layer ceramic tubes is currently under consideration. Candidate materials are alumina, dielectric constant of 9.4-9.7 and MCT, dielectric constant of 37.5-38.0. Tube lengths are 70-100 mm. The tube thickness is 1-3 mm. We have to develop a special technology for thinner tube manufacture when the tube thickness is in the 0.6-0.9 mm range, for tube length of 40-60 mm. The basis of this technology is a double-stage forming of the ceramic tube with hydraulic and isostatic pressing, sintering up to the zero water absorption point, a final mechanical treatment of the inner and outer surface and finally ceramic tube edge machining.

The following ceramic materials are in use for ceramic tube manufacturing: Al_2O_3, MgO-CaO-TiO_2, BaO-TiO_2, $CaTiO_3$-$LnAlO_3$. The loss factor of alumina does not exceed 1×10^{-4} at 10 GHz; that of MCT and the other materials mentioned above have loss factors in the range of $(1.5\text{-}2.5)\times10^{-4}$ based on our measurements at 10 GHz.

MODE SELECTIVE COUPLER

As we mentioned above, our design for a multilayered DLA structure operates in the TM_{03} mode. Therefore, it requires a TE-TM coupler that implements a direct transformation of the TE_{10} mode in the rectangular waveguide from the RF source to the TM_{03} mode in the cylindrical DLA structure. Usually, high order mode converter leads to a high conversion loss because of the over-moded propagation. Fortunately, due to the dispersion of this class of structures, the propagation constant β values for TM_{01}, TM_{02}, and TM_{03} modes are quite different from each other [3]. This means that their guided wavelength values allow us to filter the unwanted TM_{01} and TM_{02} modes out of the DLA structure. The most intuitive approach for this problem will be described below.

Let consider β_1, β_2, and β_3 as the propagation constants of the TM_{01}, TM_{02} and TM_{03} modes respectively. If there is another identical source located at $z=l$ (see Figure 2), then the TM_{01} wave magnitude is:

$$E_{z,TM01}(z,t) = E_{0,TM01}[1+\exp(-j\beta_1 l)]\exp(-j\beta_1 z + j\omega t) \quad (4)$$

If we choose the length l according to $\beta_1 l=(2n+1)\pi$, then the TM_{01} mode will be canceled out in the waveguide at distances of $z>l$. Another pair of identical sources centered at l_2 with $\beta_1 l_2=(2n+1)\pi$ then cancel out the TM_{02} mode from the rest of the guide. In this configuration, the only surviving mode in the waveguide will be the TM_{03} mode.

A variation of this scheme would be to use a set of chokes on the upstream side of the TE-TM mode converter to reflect the TM_{01}, TM_{02} and TM_{03} modes at different phases and use this reflected signal which consists of the TM_{01} and TM_{02} modes from upstream to cancel the TM_{01} and TM_{02} modes downstream.

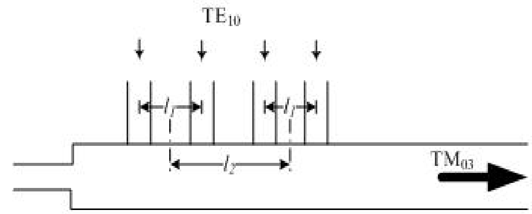

Figure 2: Schematic drawing of mode selective coupler.

SUMMARY

Using the Bragg fiber concept we propose a multilayered dielectric-loaded accelerating structure to reduce the strong accelerating field attenuation in a single layer DLA structure. We presented our results on the development and demonstration of a multilayer 34.272 GHz DLA based on new multilayer technology that provides significant reduction in wall losses and makes the DLA structure performance comparable to a conventional accelerator.

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