

DEVELOPMENT OF DUAL LAYERED DIELECTRIC-LOADED ACCELERATING STRUCTURE*

C. Jing[#], A. Kanareykin, Euclid Techlabs, LLC, Solon, OH 44139, U.S.A.
S. Kazakov, KEK, Tsukuba, Japan

Abstract

Due to the high magnetic field-induced surface currents on its conducting sleeve, a conventional single layer Dielectric-Loaded Accelerating (DLA) structure exhibits a relatively high RF loss. One possible way to solve this problem is to use multilayered DLA structures. In these devices, the RF power attenuation is reduced by making use of the Bragg Fiber concept: the EM fields are well confined by multiple reflections from multiple dielectric layers. This paper presents the design of an X-band dual layer DLA structure as well as the results of bench tests of the device. We will also present results on the design, numerical modeling, and fabrication of structures for coupling RF into multilayer DLAs such as a novel TM_{03} mode launcher and a TM_{01} - TM_{03} mode converter using dielectric-loaded corrugated waveguide.

INTRODUCTION

Dielectric loaded accelerator (DLA) structures excited by a high current electron beam or an external high frequency high power rf source have been under extensive study for the past two decades. The basic rf structure is simply a tube of dielectric surrounded by a conducting cylinder. Such a simple geometry makes dielectric-lined waveguides attractive candidates for high frequency accelerating structures, where it is expensive and difficult to precisely fabricate conventional iris-loaded copper structures. However, one of the major concerns for the conventional DLA scheme is its relatively high field attenuation per unit length. This is caused by strong magnetic fields at the metal wall, which in turn give rise to large surface currents and hence large attenuation. Our challenge is then to find a way to reduce this attenuation.

The proposed multilayered structure using the Bragg Fiber concepts represents an extremely promising approach to the solution of this problem [1]. The structure is a cylindrical waveguide which consists of a vacuum core surrounded by dielectric tubes of alternating high or low permittivity enclosed in a metal jacket. This configuration can reduce the power attenuation caused by wall losses from typically 7-8 dB/m to as low as 2.0 dB/m for X-band DLA structures and 4.0 dB/m for Ka-band [2]. In this article, we will briefly present the design, fabrication, and bench test of an X-band dual layer DLA structure.

X-BAND DUAL LAYER DLA STRUCTURE

A prototype 11.424 GHz dual layer DLA structure has

been developed by a collaboration of Euclid Techlabs LLC and the AWA group at Argonne National Laboratory to demonstrate rf loss reduction for this structure. The structure operates at the TM_{03} mode and has and its parameters are 3 mm vacuum channel radius; 5.17 mm first ceramic layer radius ($BaTi_4O_9$, $\epsilon_r = 37$); 12.02 mm outer layer radius (Al_2O_3 , $\epsilon_r = 9.7$). Its accelerating parameters have been presented in [5]. Fig. 1 shows a sample of the dual layer dielectric tube. A unique technology for the fabrication of dielectric tubes (a combination of hydraulic and isostatic pressing) ensures the homogeneous compression of the material along the tube length resulting in high precision geometrical parameters and high performance dielectric characteristics of the tubes (uniformity of ϵ and loss tangent along the waveguide length).



Figure 1: Double layered ceramic tube for the X-band dual layer DLA structure.

Each layer of the dielectric tube is made separately. The mechanical gap between the inner and outer layers is defined by the surface finish of the waveguides. The inner surface of the outer alumina layer was polished to an accuracy of 3 μm that meets the mechanical tolerance requirements for the ceramic loading of the accelerating structure. However, it should be noted that the field enhancement of the electrical field radial component in the gap can be effectively suppressed because the proper choice of the dielectric constant values and dielectric thickness of the layers provide a null in the transverse electric field at the gap. Fig. 2 plots the analytical results of the longitudinal and transverse components of the electrical field for the accelerating mode along the radial direction. An exaggerated gap (50 μm) is considered in the analysis, where we can see the field enhancement is rather low for the accelerating mode because the gap position is located at the node of transverse electric field E_r . The electric field enhancement ratio may be larger for the hybrid modes, but they can be easily damped [4].

*Work supported by US DOE SBIR Grant No. DE-FG02-05ER84356.

[#]jingchg@hep.anl.gov

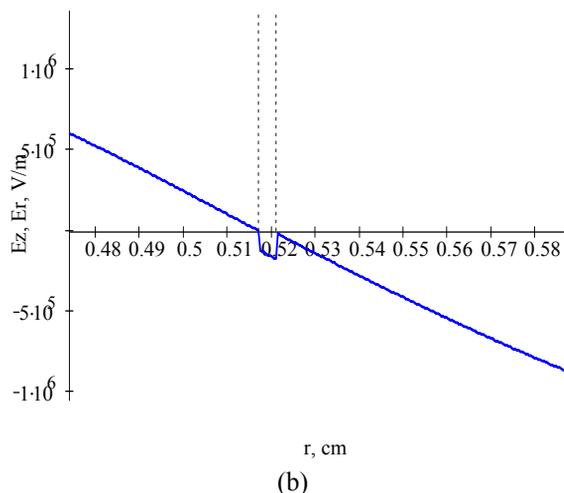
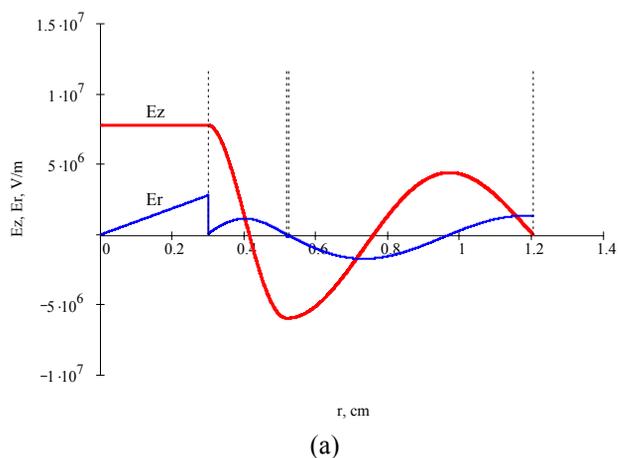


Figure 2: a) Longitudinal and transverse electric field profiles of the TM_{03} mode for the double layer DLA 11.424 GHz structure; b) Expanded plot of the transverse electric field E_r at the gap.

Mode Launcher Designed for Bench Test

The developed dual layered DLA structure operates on the TM_{03} mode. We have designed a new TM_{03} mode launcher for the bench test of the structure. It consists of a triple layered coaxial waveguide which can generate the similar magnetic field pattern to that of the TM_{03} mode in the DLA structure. They also share the same dielectric material for better impedance matching. The bench measurement of the X-band TM_{03} mode launcher and the dual layered DLA structure is modeled in CST Microwave Studio® (shown in Fig. 3). The simulation shows that it has $S_{11} = -20.7$ dB, $S_{21} = -0.03$ dB at the center frequency 11.424 GHz with a bandwidth > 50 MHz. The fabricated TM_{03} mode launcher is shown in Fig. 4. We can see the each dielectric ring has one end tapered for impedance matching. The copper part in the middle works as a support when the mode launcher is attached to the dual layer dielectric-loaded waveguide.

Bench Measurement

We used a Vector Network Analyzer to characterize the RF transmission and reflection of the dual layer DLA

structure in the required X-band frequency range. These measured S-parameters verified our simulation results and allowed us to obtain the power attenuation data for the double layer DLA accelerator.

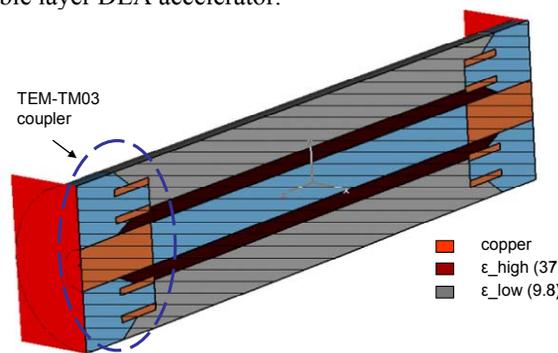


Figure 3: 3D model of the bench test of the X-band dual layer DLA structure.



Figure 4: The fabricated TM_{03} mode launcher for the bench test of the dual layer DLA structure: components (left) and assembly (right).

We fabricated 5 double layer ceramic tubes, each 7 cm long. During measurement, we first tested the structure with one ceramic waveguide loaded in. The results obtained have been used as our baseline, or calibration of the TM_{03} mode launcher presented in the previous section. Then we loaded the second piece of double layer ceramic tube, and measured both the transmission and reflection coefficients again. The subtracted value of the transmission was the calibrated rf loss factor value for the 7 cm dual layer DLA structure.

Measurement data for the single double layer waveguide is presented in Fig. 5. Simulation results are also plotted for comparison. One can see that both simulation and experimental data are in a good agreement except for the larger transmission value obtained in the simulation, easily understandable because the rf losses of the copper section and dielectrics were not taken in account in the simulation. For a one piece ceramic tube, S_{21} is -1.08dB at 11.424 GHz; and for 2 pieces, S_{21} is -1.35dB at 11.424 GHz. Both cases have very small S_{11} (less than -15dB). Therefore, the transmission loss of one 7 cm long dual layer ceramic waveguide is 0.27 dB. Based on this result, the predicted power attenuation for the dual layer DLA is less than 4 dB/m for the X-band double layer ceramic-based accelerator.

The measured 4dB/m rf attenuation is slightly higher than the theoretical expectation of 2.7 dB/m. Further investigation shows that two factors may contribute to this discrepancy: 1) the loss tangent of the dielectric material is a slightly higher than assumed. For example, the

attenuation can go to 3.5dB/m if the loss tangent of the inner layer ceramic tube is over 2×10^{-4} ; 2) the roughness of the inner surface of the copper wall leads to more losses, even though the magnetic field on the copper surface is very small.

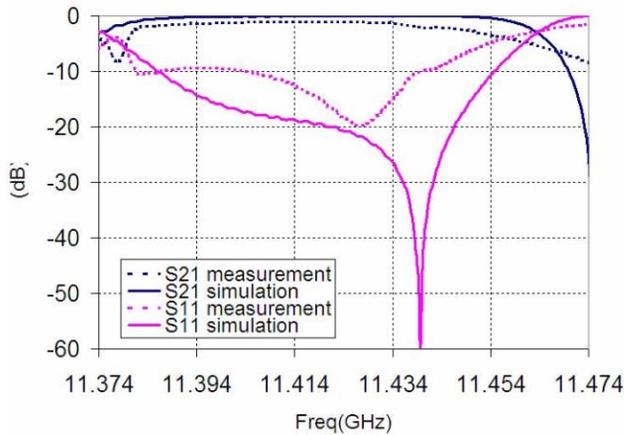


Figure 5: Results of the bench testing and simulation of the structure with a single segment of double layer ceramic tube loaded in.

Mode Converter Designed for High Power Test

To be able to perform the high power testing of the proposed dual layer DLA structure, a mode converter is needed to transform the TE_{01} mode of the rectangular output waveguide of the X-band NRL Magnicon to the TM_{03} mode of the circular dielectric loaded waveguide. The proposed solution consists of two parts, a TE_{10} to TM_{01} mode converter and a TM_{01} - TM_{03} mode converter. The TE_{01} - TM_{01} mode converter has already been successfully tested [3]; here, we briefly introduce the design of TM_{01} - TM_{03} mode converter.

The TM_{01} - TM_{03} mode converter is based on the specific dielectric loaded corrugated waveguide shown in Fig. 6, where a double layer dielectric tube slides into a corrugated waveguide for matching the impedance. The periodically varying radius of the corrugated waveguide provides the mode transformation from the TM_{01} to the TM_{03} cylindrical waveguide mode. In principle, any non-uniformity along the waveguide, such as varying radius or axis bending in the circular waveguide will lead to energy exchange among the various guided wave modes resulting in mode transformation of the propagating rf wave. As long as the azimuth angle does not change and the radius varies along the axis of a circular waveguide, the transverse magnetic mode TM_{mn} can be converted only into another transverse magnetic $TM_{m'n'}$ mode. In addition, to build up a directional mode conversion between two specific modes and simultaneously suppress others, a periodic geometric perturbation along the waveguide must be established, and its period λ_w must satisfy the following equation:

$$\Delta\beta = \beta_1 - \beta_2 = l \frac{2\pi}{\lambda_w} \quad l = \pm 1, \pm 2, \dots \quad (1)$$

where β_i is the propagation constant of the i^{th} mode. For $l=1$, the period of the geometric perturbation is the beat wavelength of the two converted modes, which can make the energy of the required mode increase along the waveguide. The length of mode converter is $L = N\lambda_w$, where $N=1,2,\dots$ is determined by the required transfer efficiency, frequency bandwidth, and perturbation strength.

Figure 7 shows the simulation results of a TM_{01} - TM_{03} mode converter, which has $N=6$ and $\lambda_w=15.4$ mm. Instead of using a corrugated copper housing, we modeled a corrugated outer layer ceramic tube for simulation, which has an equivalent effect. The conversion efficiency has reached 95% within the pass band for TM_{01} - TM_{03} mode transformation, and the TM_{02} mode has been effectively suppressed.

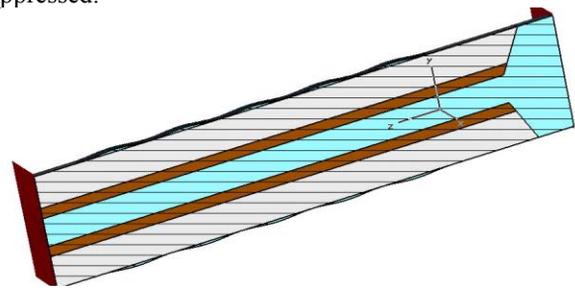


Figure 6: Dielectric loaded corrugated waveguide providing the TM_{01} - TM_{03} mode conversion.

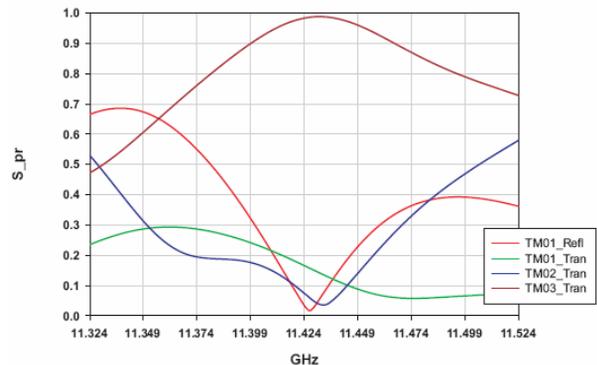


Figure 7: Simulation results for the TM_{01} - TM_{03} mode converter.

REFERENCES

- [1] C. Jing, W. Liu, W. Gai, J. Power and T. Wong . *NIM-A*, 539, (2005) pp.445.
- [2] W. Liu, C. Jing, W. Gai, etc. *Proc. PAC 2003*, Portland, May, 2003, pp.1810-1812.
- [3] A. Kanareykin, C. Jing, P. Schoessow, W.Gai, and J. Power, *Proc. EPAC'06*, Edinburgh, July 2004, p. 2466-2468.