DESIGN AND EXPERIMENTAL INVESTIGATION OF AN X-BAND MULTILAYER DIELECTRIC ACCELERATING STRUCTURE*

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Abstract

One practical concern in the performance of the conventional (single layer) dielectric loaded accelerator (DLA) structure is its relatively high field attenuation per unit length. We present a new project to significantly improve the efficiency of high gradient DLA structures. We have been developing a *multilayer* DLA where the single dielectric layer is replaced by a multiple coaxial layers of differing permittivity. The power attenuation in the multilayer structure is reduced using the Bragg Fiber principle where the dielectric layers are used to create multiple reflections in order to confine the accelerating mode fields for the most part in the dielectric, reducing the axial current on the conducting outer boundary. A design for an X-band multilayer structure operating in the TM_{03} mode using alternating dielectric layers with permittivities of 37 and 9.7 is discussed. Bench test results for a multilayer 11.424 GHz structure are presented.

BRAGG FIBER CONCEPTS FOR DIELECTRIC BASED ACCELERATORS

Dielectric loaded accelerator (DLA) structures excited by a high current electron beam or an external high frequency high power RF source have been studied extensively for many years [1]. The conventional DLA structure consists of a dielectric-lined cylindrical waveguide driven by an external microwave source. This structure can be operated as a slow-wave, traveling wave (TW) accelerator. However, a major concern for the conventional DLA scheme is its relatively high field attenuation per unit length. This is caused by strong magnetic fields at the outer conducting boundary, which in turn give rise to large surface currents and hence large attenuation. Normally, one prefers high dielectric constant materials to keep the group velocity of the wave low in order to maximize the shunt impedance per unit length. However, high dielectric constant materials further increase the attenuation. Our challenge is then to find a way to reduce the attenuation while simultaneously keeping the shunt impedance high.

The use of a multilayered structure represents an extremely promising approach to the solution of this problem. A multilayer DLA structure designed using the Bragg Fiber concept will reduce the power attenuation caused by the wall losses from typical 7-8 dB/m to as low as 2.0 dB/m for 11 GHz and 4.0 dB/m at 34 GHz [2-3]. This new approach will allow us to overcome the major difference in power attenuation between conventional iris-loaded structures and new DLA structures while keeping all the benefits of dielectric loading: simplicity of fabrication, maximum electric field magnitude along the structure axis, smaller BBU effects and reduction of coupled bunch effects [2-3].

It should be noticed that the double layer DLA design allows the suppression of field enhancements between two ceramic layers by proper choice of the dielectric constant values and dielectric thickness of the layers. Another great advantage of the Bragg Fiber design is that the double layer geometry gives additional free parameters that can be used to provide a null in the transverse electric field at the gap between two dielectric layers of the structure.

Previous work in the optical regime on the Bragg Fiber (a hollow-core, multilayered, dielectric-lined cylindrical waveguide) has shown that this device is capable of low-loss and high-power transmission. A general method for solving for the fields in a cylindrical waveguide consisting of radially periodic layers of dielectrics was developed [4-6], but in these calculations the analysis was confined to non-accelerating TE or HEM modes.

We have extended the Bragg Fiber concept to the microwave regime in order to develop low-loss accelerating structures with high shunt impedance. We refer to this microwave device as a multilayered DLA structure. A vacuum channel is surrounded by multiple dielectric layers in a cylindrical metallic waveguide (Fig. 1). The dielectric layers serve as multiple reflectors that are used to reduce the magnetic field strength on the copper wall, thus making it possible to reduce the wall losses, and hence the attenuation. However, instead of trying to achieve total field confinement of the leaky modes with an all dielectric structure (which requires many dielectric layers) the multiple layers are only used to reduce the attenuation to an acceptable level, while total confinement of the fields is still achieved by the metallic wall.

MULTILAYER DLA DEVELOPMENT

We first developed a general analytic model of the TM and HEM modes in a multilayer DLA structure. This approach used recursive transfer matrices to match boundary conditions at the interfaces between layers [2]. The multilayer DLA model was incorporated into an optimization code that was used to design the test structure.

The desired operating frequency (11.4 GHz) and permittivities of the low loss ceramics to be used were used as input to the calculation. For the sake of simplicity only two and four layer configurations were considered. It was found that a two layer device was perfectly adequate

*Work supported by USDOE
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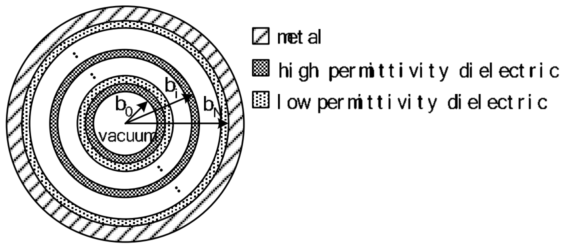

Figure 1: Cross-section of the multilayered dielectric-loaded accelerating (DLA) structure. The structure is a cylindrical waveguide which consists of a vacuum core with radius b_0 surrounded alternating high and low permittivity dielectric tubes with outer radius b_i. A conducting jacket encloses the structure.

to demonstrate the Bragg fiber effect. The vacuum channel of the test structure has a radius of 3 mm, the outer radius of first ceramic layer (permittivity= 37) is 5.17 mm, and the outer layer (permittivity = 9.7) is 12.02 mm. The corresponding materials are barium tetra-titanate and alumina respectively. Both materials possess loss tangents in the few 10^{-4} range.

In order to achieve minimal wall losses it was also necessary to operate the structure on the TM_{03} mode. In turn this required the design and construction of mode couplers to adapt the TE_{10} mode of the feed waveguide (for high power testing at NRL) and the TEM mode (for network analyzer measurements) to the TM_{03} mode in the structure.

Mode Coupler Design

We have developed a modular design to solve the high power TM_{03} conversion problem. The proposed solution consists of two parts, a TE_{10} to TM_{01} mode converter and a TM_{01}-TM_{03} mode converter. The design is based on the functional requirements that the coupler be vacuum sealed; capable of handling high power rf; maximum rf transmission at the operating frequency of 11.424 GHz with S_{21}>-1dB (in simulation) and minimum reflection S_{11}<-20 dB (in simulation); and a relatively broad bandwidth (BW 3dB >100 MHz).

The TE_{01}-TM_{01} mode converter is the first section of the TE_{01}-TM_{03} coupling section required for high-power testing of the multilayer structure. One can maximize the efficiency of conversion from the dominant TE_{10}, mode of the rectangular waveguide to the accelerating TM_{01} mode of the circular waveguide by optimizing the geometric parameters of the device. The bandwidth of the structure exceeds 800 MHz with a reflection coefficient less than -20dB and transmission S_{21} close to 0 dB, which means that nearly 100% of energy from the rectangular TE_{10} mode has been converted into the circular TM_{01} mode.

The second functional part of the TE_{10}-TM_{03} coupling section is the TM_{01}-TM_{03} mode converter that is based on a specific dielectric loaded corrugated waveguide designed by Euclid Techlabs. A double layered dielectric tube slides into a corrugated waveguide for matching the

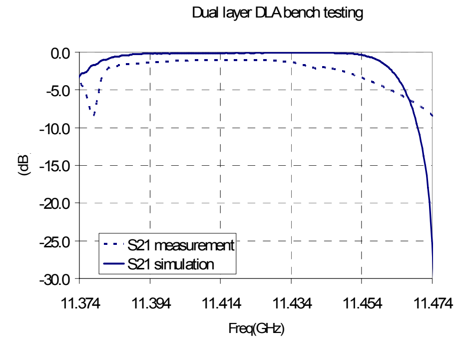

Figure 2: Comparison of the results of the bench testing and the rf transmission simulation of the structure with a single section of double layer ceramic tube.

impedance to the double layer DLA structure. The periodically varying radius of the corrugated waveguide provides the mode transformation from the TM_{01} to the TM_{03} cylindrical waveguide mode.

In the proposed TM_{01}-TM_{03} coupling section design, we use a dielectric-loaded corrugated waveguide to convert to the required mode along with providing a good impedance matching. The loading material has been chosen to be the same as that of the double layer ceramic tube used for DLA structure loading. An inner taper at the input end was used to match the impedance of the TE_{10}-TM_{01} mode converter.

Table 1: Two-layer DLA parameters

PARAMETER	**Value**
Frequency	11.424 GHz
Inner Radius	3mm-5.17mm
Outer Radius	12.02mm
Dielectric Constant	37-9.7
Dielectric tube length	70mm/piece
Group Velocity	0.064c
R/Q	2040Ω/m
Shunt Impedance	12.5 MΩ/m
Power ATTN	**2.7dB/m**

Double Layer Structure Fabrication and Testing

We have developed ceramic materials that are optimized for the experimental demonstration of the multilayer DLA structure. Microwave low-loss ceramics based on Al_2O_3 (alumina) and $BaTi_4O_9$ (barium tetra-titanate) systems with additives have been sintered using a solid-phase synthesis method. The ceramic composition showed unique parameters characterized by a homogeneous fine-grained structure and minimum porosity. The measured values of the dielectric constant of the samples especially designed for this testing were in the range of 9.7 and 37 for alumina and barium titanate respectively. Dielectric loss factors have been measured by the dielectric loaded resonator method and were found to be in the 1-3×10^{-4} range at X-band. We have designed a double layer dielectric (ceramic) waveguide operating at the TM_{03} mode at 11.424 GHz and have fabricated 5 waveguide sections made of the double-layer ceramic compositions described above. Bench test measurements have been done at the Argonne National Laboratory that demonstrated the required loss factor improvement for the ceramic-based double layer DLA structure. This represents a significant achievement in terms of the development dielectric-based accelerator structures.

To solve the bench test coupling problem for TM_{03} mode generation at low input power and to provide loss measurements of the double layer DLA structure, a TM_{03} launcher needed to be designed [7]. The TM_{03} launcher is a device that transforms the TEM mode from the coaxial feed waveguide of the network analyzer into the TM_{03} mode of the double layer structure while eliminating any other mode excitation in the structure. The same launcher attached to the downstream end of the structure transfers the TM_{03} mode backward to the TEM mode of the output coaxial line. The TM_{03} launcher allows one to use vector network analyzers supplied with coaxial inputs for DLA structure power attenuation measurements.

Measurement data for a single section of double layer waveguide are presented in Fig. 2. Simulation results are shown for comparison. One can see that both simulation and experimental data are in a very good agreement except for the better transmission value predicted by the simulation, easily understandable because the rf losses of the copper section and dielectrics were not taken in account in the simulation. The power attenuation is less than 4dB/m for the X-band double layer ceramic-based accelerator. The measured 4dB/m rf attenuation is slightly higher than the theoretical numerical estimation of 2.7dB/m obtained previously using Microwave Studio®. Further investigation showed that two factors contribute to the additional loss: 1) the loss tangent of the inner layer of dielectric material was higher than for the material we used in our simulations. Our witness sample measurements showed that the loss factor of barium tetra-titanate was in the range of $< 3\times10^{-4}$ for the inner DLA layer. At the same time, the attenuation increase to 3.5dB/m if the loss tangent of the inner layer ceramic tube exceeds $2x10^{-4}$; 2) the roughness of the inner surface of the copper wall results in more losses, although the magnetic field magnitude on the copper surface is low. We used a bore scope to scrutinize the inner copper surface for evaluation of the copper surface roughness contribution to the total DLA loss factor value. A large rough patch and scratches in some places along the tube were present. We believe that the latter had the main impact on the experimental value of the double layer DLA attenuation.

SUMMARY

A multilayer X-band DLA structure has been designed and tested using two ceramic layers with dielectric constants of 37 and 9.7 respectively. An overall double layer DLA structure power attenuation of 4dB/m has been demonstrated. The origin of the larger than predicted value of the attenuation is understood as resulting from both a structure imperfection and a higher than expected ceramic loss tangent. We plan to proceed with high power rf testing of the structure at the NRL X-band facility.

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