APPLICATIONS OF COMPACT DIELECTRIC BASED ACCELERATORS*

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Abstract

Important progress on the development of dielectric based accelerators has been made both experimentally and theoretically in the past few years. One advantage of dielectric accelerators over their metallic counterparts is their compact size, which make them attractive for industrial or medical applications. In this article, we discuss the design of dielectric based accelerators focusing on those technologies relevant toward these needs.

DIELECTRIC LOADED ACCELERATOR

The first studies of using RF driven dielectric-loaded circular waveguide for particle acceleration can be traced back to the early 1950's [1]. In recent years, because of its geometrical simplicity and availability of low loss dielectrics, theoretical and experimental investigations on dielectric based accelerators have been intensively revived. Among them, externally powered Dielectric-Loaded Accelerators (DLA), dielectric wakefield accelerators, and dielectric laser accelerators have attracted the most attention. In this paper, we concentrate on externally powered DLA technologies and possible application.

DLA structures can be made as simple as a dielectric tube surrounded by a conducting cylinder. Most of them use uniform, linear ceramic tubes so that they work as constant impedance accelerating structures. The TM_{01} mode (traveling wave accelerator) or TM_{01n} mode (standing wave) are the fundamental accelerating modes. Unlike conventional metallic accelerating structures, DLA structures do not require any structure periodicity to slow the phase velocity of the guided wave below the speed of light. For a given radius, the phase velocity of each guided wave mode in a DLA structure is governed by the dielectric constant of the material and its wall thickness. In general, for the same a/λ, where a is the radius of the beam opening and λ is the wavelength, the DLA structure can be made much smaller than a disk-loaded accelerating structure due to the high dielectric constant of the material used. This small size may be favored for applications with tight space requirements. It also facilitates the use of quadrupole lenses or a permanent solenoid around the structure to prevent the beam from breaking up in the case of high current beam acceleration. For example, for an X-band structure, given $a/\lambda=0.156$, the diameter of a cell of a 120-degree traveling wave disk-loaded accelerating structure is larger than 2 cm, but the outer diameter of the dielectric tube in a DLA structure is only 1 cm if the dielectric constant of the tube is 20.

However, the choice of dielectric constant should be considered as far more complicated than the requirement of a reduced transverse dimension. It is strongly linked with other accelerating parameters as well. A very good estimate of the group velocity of a traveling wave DLA structure is given by $V_g/c \approx 1/\varepsilon_r$ (where c is the speed of light and ε_r is the relative dielectric constant of the loaded material) when a/λ is less than 15%. The quality factor of a DLA structure can be roughly estimated as $Q \approx 5.22\times10^4/\{\sqrt{[f<GHz>\times(\varepsilon_r-1)]}+5.22\times10^4\times\tan\delta\}$, where f is the frequency of the TM01 mode in units of GHz and $\tan\delta$ is the loss tangent of the loaded material.

PARAMETER CHOICE

DLA structures are generally preferred for use in a short structure powered by short, high frequency RF pulses, which reduces the probability of RF breakdown but needs a short filling time to achieve a high RF-to-beam efficiency [2]. Consider the rough design of an X-band travelling wave DLA structure. From the group velocity estimate, we choose $\varepsilon_r=10$ for a structure with V_g=10% c. Then Q can be estimated to be 3400. Since the size of the beam opening (2a) is independent of Q but tightly related to the R/Q (figure of merit of an accelerating structure) and shunt impedance R (they both increase as the beam opening decreases), we can choose a as small as the beam emittance allows to obtain both a large R/Q and R. Meanwhile the filling time (defined as L/V_g, where L is the length of the structure) remains short since the group velocity is unrelated to the beam opening. It should be pointed out that a/λ of DLA structures cannot be chosen too small since it will increase the wakefield and thus the risk of beam break-up.

Transverse wakefield damping in DLA structures has been well studied [3]. Its implementation is rather simple: an axially slotted copper jacket filled with RF absorber or metallized strips on the outer surface of the dielectric tube surrounded with RF absorber. The low Q of the DLA structures also helps the damping of long range wakefields.

Figure 1 shows a few parameters of X-band (11.7GHz) travelling wave DLA structures. Three different dielectric constants are used in the plots, representing three commonly used low loss materials: Alumina (ε_r=10, $\tan\delta=1\times10^{-4}$), MgCaTiO ($\varepsilon_r$=20, $\tan\delta=1\times10^{-4}$) and Quartz ($\varepsilon_r$=3.8, $\tan\delta=6\times10^{-5}$). Figure 1(a) clearly shows that the group velocity is bounded by the reciprocal of the dielectric constant as the beam opening decreases. The quality factor of a DLA structure is the combined contribution of metal wall losses and dielectric losses, but

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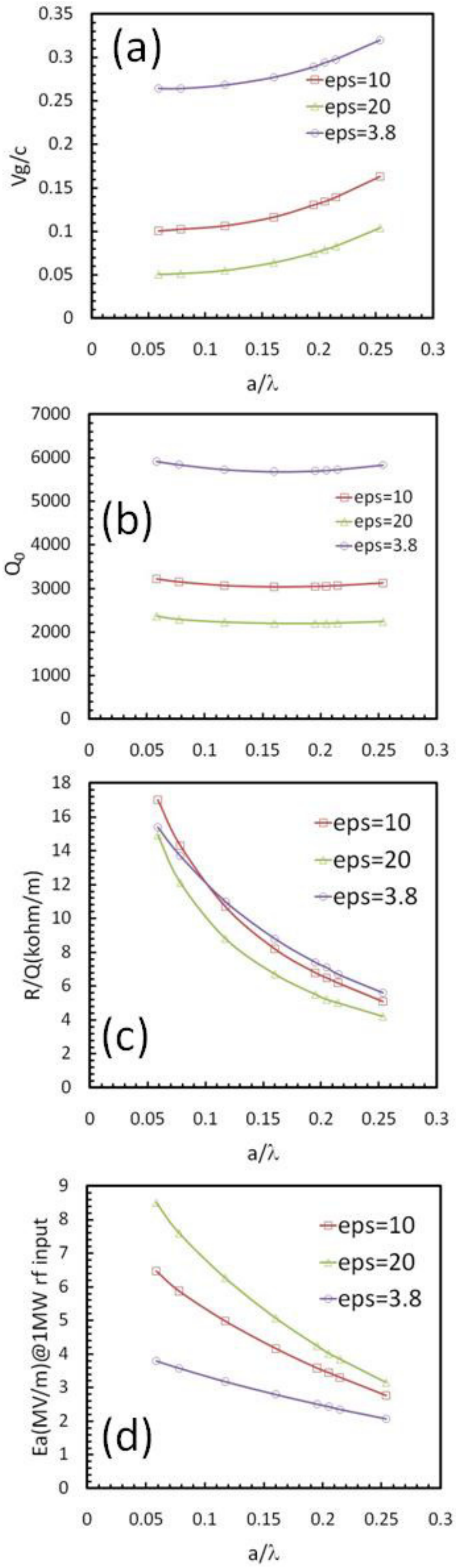

Figure 1: Dependence of parameters in DLA structures on the scaling parameter a/λ: (a) group velocity; (b) quality factor; (c) R/Q; (d) accelerating gradient.

it remains nearly constant across different size of beam channel (Fig. 1b).

From Fig. 1(c) and 1(d) we can see that the R/Q values for different dielectrics can approach or cross each other for small beam channels but the gradient in a higher ε_r DLA structure is always higher. This is because of the strong dependence of the gradient E_a on the group velocity, $E_a^2=[R/Q]\times 2\pi f\times P/V_g$, where P is the input RF power. Again, the low V_g leads to a long RF filling time which then requires a longer RF pulse to power the structure and accelerate the beam. The strong pulse length dependence of the RF breakdown rate will limit the accelerating gradient. However, in an application that does not need to operate with the gradient at a high risk level, a high dielectric constant material should be preferred since it will provide a higher gradient for a given RF power.

MULTIPACTOR

One principal effect that has limited further advances in DLA technology in the past is the problem of multipactor. The fraction of the power absorbed at saturation in the DLA structure was found to increase with the incident power, with as high as 30% of the incident power per unit length being absorbed if the dielectric material has a high Secondary Electron Yield (SEY). A thin film TiN coating, which reduces SEY, can reduce the multipactor loss below 10%. Using geometric factors, particularly the introduction of surface grooves to reduce the multipactor in DLA structures is also under investigation. However, lessons from other work show that one challenge to the success of this approach is the strong dependence upon a few critical dimensions of the groove design, which leads to a very tight machining tolerance and in turn increases the fabrication difficulties and costs.

In fact, the most effective approach to completely terminate multipactor is to use an external solenoid field. Analytical models, numerical simulations, and practical example in other applications have successfully demonstrated its effectiveness [4, 5]. In DLA structures, an external DC magnetic field in the longitudinal direction can continuously reduce the period for secondary electrons hopping on the dielectric surface (and thus spoil the resonance condition) when the ratio of the gyro-frequency to RF frequency is in the range of 0.7 to 1 (The gyro-frequency, Ω, is a plasma parameter; for electrons it is defined as $\Omega=eB/m_ec=1.76\times10^7B$ rad/s, where B is the magnetic field component perpendicular to the electron motion plane). It is equivalent to a solenoid field range from 2.8 kG to 4 kG for an X-band DLA structure. This approach is more attractive than other techniques since it can maintain all the advantages of regular DLA structures, and it is independent of the accelerator parameters other than the operating frequency.

TUNING

The need for frequency tuning (or phase velocity adjustment) of any accelerating structure arises from the fact that the phase velocity of the assembled accelerating structure will, in general, differ from the design phase velocity due to various sources of error. In a DLA structure, these errors can be caused by machining tolerances of the dielectric dimensions, thermal expansion of the structure, dielectric constant heterogeneity, etc. The common way of tuning all-metal structures is using temperature variation or slight mechanical deformation of the accelerating structure walls. The DLA structure does not admit this possibility because the ceramic loading is usually made of a brittle microwave thermostabilized ceramic that does not allow any noticeable mechanical adjustment of its geometrical parameters. At the same time, the permittivity of BST ($Ba_xSr_{1-x}TiO_3$) ferroelectric has a strong temperature dependence. If a thin, low loss ferroelectric layer having relatively high dielectric constant ($\varepsilon_r>100$, $\tan\delta<5\times10^{-3}$) is introduced, the DLA structure can be easily tuned by controlling its temperature. Introducing a relatively thin ferroelectric layer does not change the basic accelerating structure parameters significantly but it makes the overall average permittivity of the dielectric loaded resonator tunable in the range from tens of kHz to tens of MHz depending on the thickness of ferroelectric material [6].

RF COUPLING

Besides the dielectric loaded section, a DLA structure requires a RF coupler to feed in the high power RF signal. A well designed coupler should possess a high mode conversion efficiency (e.g. TE_{10} mode in rectangular waveguide to TM_{01} mode in DLA structure), and be less susceptible to high power breakdown. Figure 2 show three coupling schemes commonly used in DLA structures. In Fig. 2(a), the metallic RF coupler is separated from the DLA section. The tapered dielectric matching section is a part of the DLA structure that matches the impedance of the TM_{01} mode between the empty and dielectric-loaded waveguide. This coupling method can reach a very broad bandwidth at a cost of the extra length of the dielectric taper. It is worth pointing out the importance of fabricating the entire dielectric tube in a single piece. Any micro gap caused by a dielectric joint is subject to RF breakdown due to the strong field enhancement. Figure 2(b) shows a coaxial type coupling, where the impedance matching is accomplished in the coupler section so that the DLA section remains a simple straight tube. This design is very effective and compact, but the beam hole in the inner conductor of coaxial coupler may limit its usefulness in high gradient applications (i.e. where a/λ is small). Figure 3(b) shows a variation of the side coupling configuration, which is simple in fabrication but generally exhibits a smaller bandwidth than the axial coupling.

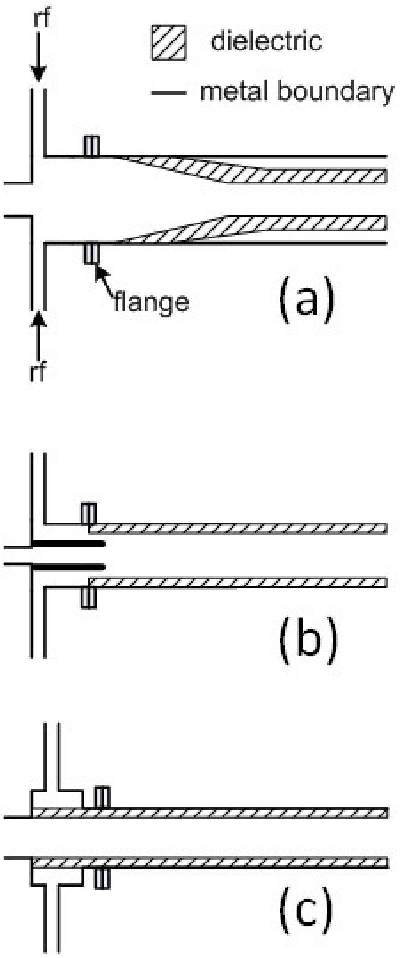

Figure 2: Three commonly used RF coupling schemes in DLA structures; (a) mode launcher; (b) coaxial coupler; (c) side coupling.

REMARKS

DLA technologies have seen significant progress for a decade. At present, it is possible to build and use a practical DLA structure. We expect that its compactness and low cost will eventually make it broadly useful in many applications.

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