An Optimal Design for a THz Slab-Symmetric Dielectric-Loaded Accelerator

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Abstract. A slab-symmetric dielectric-loaded accelerator structure, consisting of a vacuum gap between dielectric-lined conducting walls, is analyzed theoretically and computationally. The device is to be resonantly excited by an external laser source of wavelength 340 µm. Analytical results for infinite and finite-width geometries are summarized, and 2D electromagnetic simulation is used to demonstrate the time-dependent filling of the structure from the external source. The resonant accelerating fields, which are nearly constant along the short transverse direction, are found to have between 10 and 15 times the amplitude of the driving radiation, with only a small (< 10%) admixture of other non-accelerating modes. Field gradients are near 100 MV/m when the structure is driven with 100 MW of terahertz power. The resonance is highly dependent on the geometry of the slots used to couple radiation into the structure, with effects on the overall $Q$-factor, frequency detuning, and field pattern. Possible manufacturing methods are discussed, along with an all-dielectric version of the design that would allow scaling of the structure to a wavelength of 10 µm.

INTRODUCTION

Slab-symmetric structures have recently generated interest as both radiation- and beam-driven accelerators [1]; their advantages include the suppression of transverse beam wakefields and insensitivity to beam misalignment as well as breakdown mitigation [2]. For several years, a slab-symmetric optically-driven accelerator that can be resonantly excited when driven by an external radiation source has been under investigation at UCLA [3,4,5]. These devices utilize dielectric loading combined with longitudinal modulation of the structure properties to generate accelerating fields on axis which are a significant multiple of the source radiation fields. In this paper, we present a detailed demonstration of the time-dependent behavior of a structure designed to resonate at 340 µm, extending previous work [5] on terahertz accelerators, with further consideration of scaling this device to the FIR regime.

The choice of 340 µm for the resonant wavelength is appropriate for a proof-of-principle experiment, since larger structure dimensions allow easy passage for an electron beam and longitudinal wakefields are negligibly small. Such an experiment will be possible in the near future at UCLA, using a planned multimegawatt terahertz radiation source under development [6].
FIGURE 1. (a) Schematic drawing of the structure geometry. Two layers of dielectric-lined conductor surround a vacuum gap; a very wide electron beam is injected into the gap and travels in the +z direction, while radiation (polarized in z) is coupled in from above through transverse slots in the conductor. (b) A cross-section in x, showing the parameters used in the analysis.

BASIC PRINCIPLES AND ANALYTICAL RESULTS

Fundamentally, the slab-symmetric accelerator consists of a pair of parallel dielectric planes, separated by a narrow vacuum gap and bounded above and below by a thin conductive layer. Periodic slots in the conductor provide a means for coupling radiation into the gap and also enforce longitudinal periodicity in the structure fields; without such modulation of the structure, only z-independent Fabry-Perot modes (equivalent to the ‘zero-modes’ of accelerator physics) will appear. When longitudinal periodicity is added and the correct resonant geometry is achieved, the mode pattern is dominated by a longitudinal standing wave having a phase velocity exactly equal to the speed of light. The concept is illustrated in Figure 1.

Any periodic modulation in the coupling or dielectric properties of the structure would serve to generate usable accelerating fields, and previous approaches to this design have each taken a different approach to generating this periodicity [3,4]. The periodic slots used here represent the optimum choice for coupling power preferentially into the accelerating mode. However, they significantly perturb the resonant frequency of the structure, as will be discussed below, and their effect on the fields must be included in the design.

If the slab-symmetric accelerator is to be scaled to laser wavelengths (e.g. 10 μm), the conductive outer layer will no longer function as a good mirror, and a different approach must be employed. It may be possible to avoid the use of metals altogether in this case by employing a Bragg reflector made from dielectric layers. A possible design for such a structure is described below.

Infinite and Finite Slab Fields: Analysis

The accelerating-mode fields for a structure with infinite transverse extent are straightforward to derive and have been presented in e.g. [4]; the effects of a finite transverse dimension are considered in [2]. In the interests of brevity, we will simply quote the relevant results here and give some comments on the form of the solutions. Using the axes and parameters defined in Fig. 1, we assume a vacuum gap of width 2a and dielectric of relative permittivity ε occupying the region from |y| = a to |y| = b.
Given the translational symmetry of the structure in \( x \), the dispersion relation forces the \( y \)-dependence of the fields to vanish for speed-of-light (synchronous, \( \omega/k_z = v = c \)) accelerating fields. This property, attractive for acceleration, also leads to the suppression of transverse wakefields during the passage of a ribbon electron beam through the structure. The accelerating fields are now simply given by

\[
E_z = E_0 \cos(k_z z) \cos(\omega t)
\]

and the allowed eigenvalues \( k_z \) satisfy a transcendental equation relating them to \( a, b, \) and \( \varepsilon \), as detailed in [3], Eqn. 3.

The most straightforward way to analyze a quasi-slab-symmetric structure of large but finite \( x \)-width is to realize that the field profile in an open structure (no sidewalls) will be determined primarily by the mode pattern of the driving radiation. Assuming a single-mode Gaussian laser beam illuminating the structure, the resulting \( x \)-dependence will have the same limiting form as a cosinusoid for small \( x \), which can be obtained if a closed structure with conducting sidewalls is employed. We can therefore approximate the field behavior near the center of the structure by assuming conducting boundaries at \( x = \pm L \), where \( L \gg b \). The mode analysis is similar, though more involved, with synchronous modes now having a hyperbolic dependence in the vacuum gap:

\[
E_z(x,y,z) = E_0 \cosh(k_x x) \cos(k_x x) \cos(k_z z) \cos(\omega t).
\]

A generalized eigenvalue equation for the allowed \( k_z \) is obtained:

\[
(1 + \varepsilon)k_x^2 + (1 - \varepsilon)k^2 = -k_x \xi (\xi \coth(k_x a) \cot[\xi (b - a)] + \tanh(k_x a) \tan[\xi (b - a)])
\]

where \( \xi = \sqrt{(\varepsilon - 1)k_z^2 - k_x^2} \); this expression reduces to the infinite-slab limit as \( k_x \to 0 \).

In a realistic experimental situation, the laser pulse width \( \sigma_r \) will naturally be much greater than the structure dimension \( a \), so that \( k_x \ll k_y \). The quantity of interest for the accelerating fields is the resultant amount of nonuniformity of \( E_z \) within the vacuum gap, i.e. the value of \( E_z(y=a)/E_z(y=0) = \cosh(k_x a) \). For a laser spot size of 10λ, roughly the smallest possible for terahertz radiation, we have \( k_x \sim 1/\sigma_r \sim 300 \text{ m}^{-1} \) and \( \cosh(k_x a) = 1.0006 \). The magnitude of \( E_x \) is likewise of order \( 10^{-4} E_z \). Clearly, this aspect ratio of \( L/a \sim 30 \) is sufficient to produce an excellent approximation to the infinite-slab fields.

**Coupling**

The coupling slots which enforce the field periodicity as well as allowing radiation into the structure are an effective way to drive the accelerating mode efficiently, but in contrast to the usual waveguide couplers employed with microwave accelerating cavities, these slots have a width which is effectively infinite, and hence they are not cut off for the relevant radiation frequency. They will thus inevitably be filled with field as the structure itself fills, with two consequences: first, there are unavoidably large fields within the slots, which become the most likely electric breakdown site, and second, the resonant frequency of the structure will be perturbed by the slots.

To estimate the effects of the slot fields, we can consider each slot to represent a parallel-plate transmission line of length \( \Lambda \) equal to the thickness of the structure's metal wall. The line is driven by wall currents on the inner surface of the structure.
boundaries and terminates in an open circuit at the outer surface. This strategy assumes that the slot width $w$ is small compared to the radiation wavelength $\lambda_0$. The driving field for the “transmission line” can be estimated from the wall current $J_x$ associated with the structure accelerating field, and will be inversely proportional to $\varepsilon_g$, the dielectric permittivity within the slot.

Consideration of the slot as a transmission line implies that setting the slot length $\Lambda$ equal to $\lambda_g/4 = \lambda_0/4\sqrt{\varepsilon_g}$ will give rise to a quarter-wave matching condition in which the slot fields vanish at the inner surface. The structure fields are then unperturbed by the presence of the slots. We will show below that simulation of structure filling under these conditions confirms this behavior, with very long filling times (large coupling $Q$).

To estimate the perturbation of the resonant frequency by the presence of the slot fields, we can employ a version of the Slater perturbation theorem. We implicitly assume that the field energy in the slots is small compared to the total field energy of the structure, which will be true for sufficiently narrow slots, and ignore the perturbation of the structure fields by the slots. Explicit calculation gives the result

$$\frac{\Delta \omega}{\omega_0} = \frac{-4\lambda_0 \sin(2k_g \Lambda)/k_g w}{\pi^4 [a\sin^2 \xi + \frac{2}{3} \varepsilon \cos \xi + (b-a)\varepsilon]}$$

where $\xi = k_z \sqrt{\varepsilon - 1}(b-a)$. Eqn. 4 predicts that for small $w$ and $\Lambda$ the frequency detuning should be proportional to $\Lambda/w$ and that there should be no detuning effect for $\Lambda = \pi(2k_g) = \lambda_g/4$, as mentioned previously.

**All-Dielectric Structure**

As mentioned, a structure without metallic boundaries would be advantageous at lower wavelength, when the thickness of the outer conductive layer would become less than a skin-depth. One approach for scaling the slab-symmetric resonant structure to near-optical frequencies is the replacement of the metal boundary by a dielectric multilayer (or Bragg reflector) arrangement. In this design, the structure $Q$ is controlled by the number of layers employed and their permittivities. Using standard formulas, we find that a nine-layer design results in reflectances for each mirror of 99.2% using permittivities of 3.6 and 11.6 (see Figure 4). The exact field distribution within the structure can only be found from simulation. Preliminary results indicate peak accelerating fields of 5–10 times the driving radiation amplitude, but nearly equal Fabry-Perot and accelerating field components.

**SIMULATION RESULTS**

In previous work, we presented eigensolutions for the fields of an infinite-width slab structure without coupling slots, showing agreement with the analysis in the previous section, and verified the vanishing of transverse wavefields using a particle-in-cell code [5]. Here, we present time-domain simulations, carried out using a custom 2D finite-difference code [4], demonstrating the effect of the coupling slots.
The theoretical dependence of the frequency perturbation on slot dimensions agrees approximately with simulation for small slot depths, though frequency resolution is limited by the simulation grid size. Further, the use of quarter-wavelength matching in the slot length to give unperturbed structure fields was verified, as shown in Figure 2, where a two-dimensional calculation shows strong fields in the slots that have no effect on acceleration fields when the slot length $\Lambda$ is approximately $\lambda_g/4$. In the same figure, these fields are compared with those of a structure with much shorter (5 $\mu$m) coupling slots. In this second case, the accelerating field is deformed in the vicinity of the slot and the resonant frequency is increased.

Figure 3 compares the relative amplitudes of the accelerating and Fabry-Perot modes for these two structures (detailed parameters of which are presented in Table 1). The quarter-wavelength slots give a structure with high $Q$-factor—the accelerating field amplitude is more than 15 times that of the drive laser—with a concomitantly long filling time (more than half a nanosecond). There is excellent mode quality, as the competing Fabry-Perot mode has less than one-half percent the amplitude of the accelerating mode. However, the field strength within the slots is also very large—more than three times the peak accelerating field at the outer end—which gives strict breakdown limitations. The 5-$\mu$m slots lead to a significantly reduced $Q$-factor and field enhancement, with noticeably poorer mode quality, but the field in the slot is less than the peak fields, and the filling time (150–200 ns) is much more realistic for an experiment driven by a short-pulse source such as would be obtained by frequency conversion of a CO$_2$ laser. The shorter pulse duration also reduces the risk of breakdown. Both structures show accelerating fields on the order of 100 MV/m when driven with a 100 MW laser source focused to a 2 cm spot.

**MANUFACTURE**

Since these dielectric-loaded structures are both planar and essentially constructed of metal and semiconductor layers, they can easily be manufactured using vapor-deposition techniques, as is done in the semiconductor industry. The main issue to be confronted is that of tunability; two possible approaches have been investigated.

**TABLE 1. Structure dimensions and filling parameters from simulation, for two versions of the 340 $\mu$m design.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Quarter-Wave Slots</th>
<th>Short slots</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vacuum gap ($2a$)</td>
<td>230 $\mu$m</td>
<td>237 $\mu$m</td>
</tr>
<tr>
<td>Dielectric thickness ($b-a$)</td>
<td>30 $\mu$m</td>
<td>17 $\mu$m</td>
</tr>
<tr>
<td>Dielectric $\varepsilon$</td>
<td>3.0</td>
<td>11.69</td>
</tr>
<tr>
<td>Slot width $w$</td>
<td>5 $\mu$m</td>
<td>20 $\mu$m</td>
</tr>
<tr>
<td>Slot depth $\Lambda$</td>
<td>69 $\mu$m</td>
<td>5 $\mu$m</td>
</tr>
<tr>
<td>Accel. field enhancement $E_{z_{max}}/E_0$</td>
<td>15.7</td>
<td>11.3</td>
</tr>
<tr>
<td>Peak accel. field per 100 MW drive</td>
<td>122 MV/m</td>
<td>89 MV/m</td>
</tr>
<tr>
<td>Fabry-Perot mode amplitude</td>
<td>0.0038 $E_{z_{max}}$</td>
<td>0.099 $E_{z_{max}}$</td>
</tr>
<tr>
<td>$1/e$ filling time $\tau$</td>
<td>335 ps</td>
<td>137 ps</td>
</tr>
<tr>
<td>$Q = \omega \tau$</td>
<td>1850</td>
<td>750</td>
</tr>
<tr>
<td>Maximum slot field</td>
<td>3 $E_{z_{max}}$</td>
<td>0.4 $E_{z_{max}}$</td>
</tr>
<tr>
<td>Frequency detuning $\Delta \omega/\omega_0$</td>
<td>0</td>
<td>+0.033</td>
</tr>
</tbody>
</table>
FIGURE 2. Surface plots of $E_z$ over one structure period in $z$, for slab symmetric structures with (left) slot length 69 µm, slot width 5 µm; (right) slot length 5 µm and slot width 20 µm. The $y > 0$ halfplane is shown; field strengths are relative to the amplitude of the driving radiation. The conductor appears as a zero-field region.

FIGURE 3. Time history of electric field amplitudes for the accelerating and Fabry-Perot modes, comparing the two slot geometries from Table 1. All fields are normalized to the amplitude of the driving radiation.

FIGURE 4. Two generalizations of the slab-symmetric structure. Left: A design for a dielectric-only structure, suitable for use at 1–10 µm. Right: Geometry (cross-section in $z$) of a monolithic slab structure capable of manufacture through vapor deposition. A second dielectric material (having permittivity $\varepsilon'$ near 1) serves as a substrate for the whole structure.
The simpler method involves constructing the top and bottom dielectric/conductor slabs separately, and positioning them correctly relative to each other using micropositioning technology. Such a structure would have open sides, much like a traditional Fabry-Perot resonator, and would need to be considerably wider than the laser spot size in order to limit diffraction of power out of the structure through the sides. In this case, we expect the resonant fields to follow the laser profile in $x$; hence any transverse ($x$-dimension) mode structure in the laser beam will tend to be imprinted on the cavity fields, which could potentially affect the phase synchronism.

An alternate construction method would use a monolithic approach, in which the top and bottom dielectrics are supported by a larger dielectric structure produced through multilayer deposition, as shown in Fig. 4. Such a design removes the need for precise external positioning if dimensional tolerances can be made sufficiently small; however, in order for the structure to be tuned through deformation the upper layer will need to be quite thin, which would be challenging to manufacture successfully. In principle, it should be possible to obtain the unperturbed infinite-width fields (i.e. Eqn. 1) within the vacuum gap, if they are correctly matched to a superposition of cavity modes in the $|x| > L$ regions.

CONCLUSION

A slab-symmetric resonant structure is an attractive optical accelerator, with usable acceleration fields of at least 10 times the driving radiation amplitude. A proof-of-principle experiment at 340 µm is planned to investigate the details of coupling radiation into the structures as well as the engineering questions regarding their manufacture. A successful demonstration at terahertz could lead to a FIR accelerator with extremely high gradients.

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REFERENCES