DESIGN OF A DIELECTRIC-LINED WAVEGUIDE FOR TERAHERTZ-DRIVEN LINEAR ELECTRON ACCELERATION

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Abstract

A dielectric-lined waveguide has been designed for use as an accelerating structure in terahertz-driven electron acceleration experiments at Daresbury. Experimental verification of acceleration will take place on Versatile Electron Linear Accelerator (VELA). The choice of a rectangular waveguide structure with sidewall dielectric layers enables tuning by varying the spacing between dielectric slabs to account for potential manufacturing errors. Schemes for coupling free-space single cycle THz pulses into the waveguide have been evaluated and optimised through CST simulation.

INTRODUCTION

The use of terahertz (THz) frequencies as an alternative to conventional RF allows for smaller, sub-millimetre structures, with higher accelerating gradients due to increased breakdown limits [1]. Optical frequencies also have this advantage, but the smaller wavelengths result in smaller structures and require manufacturing precision in the sub-micron range. THz wavelengths have the further advantage over optical that an electron bunch of higher charge can be confined within a single acceleration period. Dielectric-lined waveguides (DLWs) can support travelling-wave accelerating modes with phase velocities v_p less than the speed of light. A DLW used for acceleration must maximise interaction between the THz pulse and an electron bunch. There are several points to consider; phase matching of electrons and THz pulse over a wide bandwidth, accelerating gradient, shunt impedance, and ease of fabrication. Other issues include charging of the dielectric and electron bunch injection into a small aperture.

Typical design choice is to use a cylindrical DLW as this maximises the accelerating gradient for a given input power [2]; however this removes the potential for tunability in the case of fabrication errors. Here we consider rectangular DLWs, such as that shown in Fig. 1. The use of CVD diamond as the dielectric allows for thin, few micron dielectric layers, with the benefits of high breakdown field, low loss tangent and highest known thermal conductivity [3]. A rectangular DLW can be tuned to a different operating frequency by varying the dielectric slab separation, which has the added benefit of correcting for any manufacturing errors.

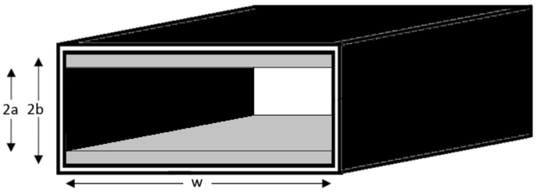

Figure 1: A hollow rectangular DLW of width w, dielectric slab separation $2a$ and dielectric slab thickness $t = b - a$. The waveguide is enclosed with metallic walls.

ACCELERATING MODE

Rectangular DLW modes are longitudinal section magnetic/electric (LSM/LSE) [4], with no H_y/E_y components (normal to the dielectric interface). Field analysis has been performed previously in [2]. The lowest order accelerating mode, with an on-axis longitudinal field component, is the LSM_{11} mode. Figure 2 shows the dispersion relation for the LSM_{11} mode of a rectangular DLW. A THz pulse propagating through the waveguide can co-propagate with an electron at frequencies corresponding to $v_p \leq c$. For an electron travelling at velocity $v_e = v_p = c$, it will travel in phase along the length of the waveguide with one frequency component of the pulse. All other frequencies will shift out of phase with the electron. The phase and group velocities for a rectangular DLW are shown in Fig. 3. To understand the effectiveness of the waveguide as an accelerating structure, figures of merit were used. Those considered of most importance were the shunt impedance, r_s, and the accelerating bandwidth, Δf. Shunt impedance is given by

$$r_s = \frac{(V_0 T)^2}{P_{diss}}, \tag{1}$$

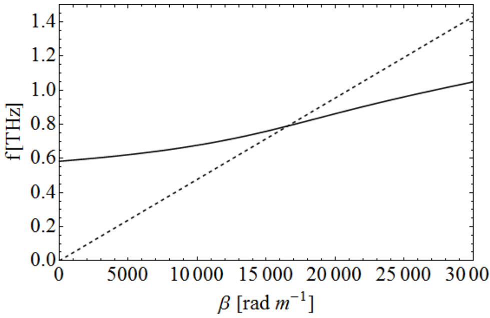

Figure 2: Dispersion relation of the LSM_{11} mode for the optimised waveguide parameters. The dotted line represents $v_p = c$.

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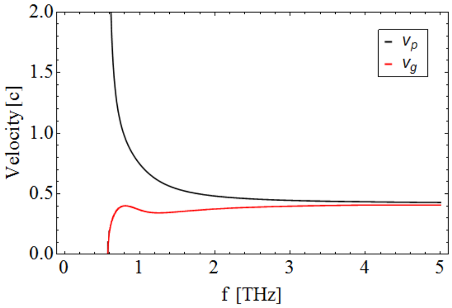

Figure 3: Phase and group velocity of input frequencies f.

where V_0 is the on-axis accelerating voltage, T is the transit time factor, and P_{diss} is the dissipated power. Δf can be approximated by the group velocity, $v_g = \frac{d\omega}{d\beta}$;

$$v_g \approx \frac{\Delta\omega}{\Delta\beta} = \frac{2\pi\Delta f}{\pi/L} . \qquad (2)$$

Δf corresponds to the range of frequencies which will slip out of phase with an electron by no more than $\pm\pi/2$ over the length, L, of the DLW. These frequencies will therefore accelerate a relativistic electron over the length of the structure. Outside of this bandwidth the frequencies will both accelerate and decelerate along the length of the structure. The centre frequency, f_{op}, corresponds to that at which $v_p = v_e$, the electron velocity which is assumed equal to the speed of light, c. Maximising Δf increases the range of frequencies of an input pulse capable of constant acceleration and therefore improves efficiency. It is also necessary to ensure the bandwidth of the input pulse overlaps with Δf. Ideally $v_g = v_e$ to ensure the input pulse envelope co-propagates with the electron, maximising the electric field amplitude experienced by the electron. However as a result of dispersion, and $v_g < c$, the electron will experience a decreasing field amplitude as it propagates through the structure.

WAVEGUIDE DESIGN PARAMETERS

The waveguide design was optimised to maximise r_s and Δf. Operating frequency and DLW dimensions were varied, with the limitation that $a \leq 100$ µm in order to allow an electron bunch to pass through the aperture. The choice of dielectric was fixed as CVD diamond and therefore $\epsilon_r = 5.68$. An operating frequency of 0.5 ± 0.3 THZ was necessary for matching to the THz source frequency. A waveguide length of 10 mm was chosen as a compromise between the bandwidth and the total accelerating voltage, although the optimum length has not yet been studied. The optimised waveguide parameters are shown in Table 1. The relatively high frequency was chosen over lower frequencies as it increased the accelerating bandwidth, and also decreased the dielectric thickness. This assumes the source bandwith is flat in amplitude, which may not be the case. The small bandwidth is expected as a result of low v_g; by reducing the length of the DLW it can be increased but this reduces the accelerating length.

Table 1: Optimised Waveguide Parameters for L = 10 mm

Operating frequency, f_{op}	0.784 THz
Dielectric slab separation, $2a$	200 µm
Width, w	600 µm
Dielectric slab thickness, t	30 µm
v_p/c	1
v_g/c	0.4
r_s	167 MΩ m^{-1}
r_s/Q	3.28
Δf	5.8 GHz

VELA Beam

VELA operates at an energy of 4.5 MeV, corresponding to $v_e = 0.9948\ c$. The previously optimised waveguide can be used with a lower operating frequency further down the dispersion relation, which will propagate with $v_p = v_e$. This corresponds to f_{op} = 0.678 THz, with r_s = 234 M Ω m^{-1} and Δf = 5.3 GHz for the dimensions given in Table 1.

WAVEGUIDE COUPLER DESIGN

The input THz pulse must be coupled into the structure from free space. Typical options are the use of focusing lenses, gratings, or horns [5]. The choice of a vertical taper coupler means that the waveguide gradually increases in transverse size until the waveguide mode matches the input THz mode. This method was considered due to the requirement of passing an electron beam through the structure and thus needing a sufficiently large aperture to prevent beam losses. Coupler design was also optimised to minimise complexity of fabrication and operation. Standard pyramidal coupler modes, with no dielectric lining, approximate to the free space THz mode created by four non-linear crystals, which increases complexity. Coupler design instead focussed on the use of dielectric as a guiding medium. Extending the dielectric slabs out of the waveguide and tapering upwards produces two separate dielectric waveguides, Coupler A and Coupler B, as shown in Figs. 4 and 5 respectively.

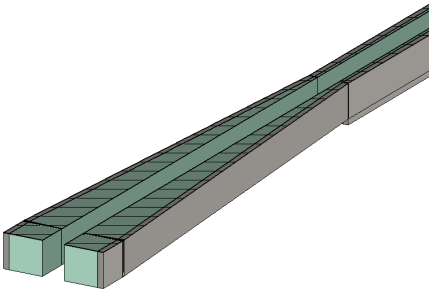

Figure 4: Coupler A, a design with metallic sidewalls. Two dielectric waveguides are separated by an aperture.

The THz pulse can be created directly at the waveguide entrance, or some distance away to allow space for focussing elements, potentially allowing very high transmission of the source to the structure. The input mode is defined by

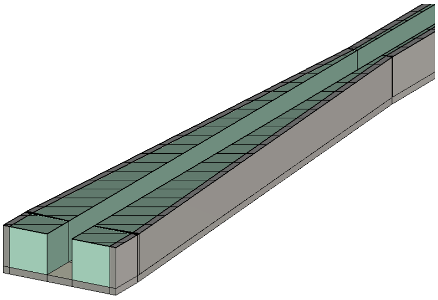

Figure 5: Coupler B, a design with all metallic walls. Two dielectric waveguides are separated by an aperture.

the boundary conditions at the waveguide entrance. Two potential input modes were established, shown in Figs. 6 and 7.

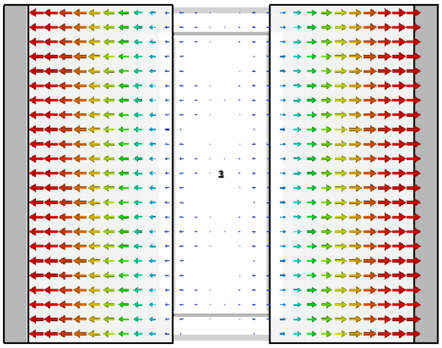

Figure 6: Input mode of a coupler with metal on the side walls only. There is a small longitudinal field component on-axis which is shifted in phase by π compared to the transverse components.

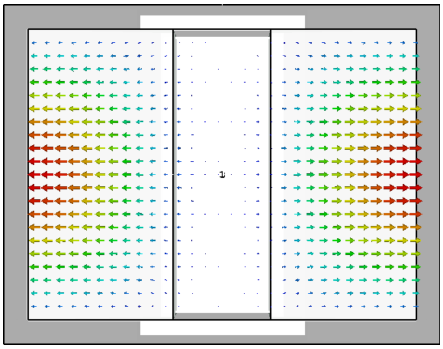

Figure 7: Input mode of a coupler with metal enclosing the coupler. There is a small longitudinal field component on-axis which is shifted in phase by π compared to the transverse components.

Input THz Pulse

A method of THz pulse production has been demonstrated by Cliffe [6]. The transverse field pattern is similar to a HG_{01} mode, with a longitudinal electric field component on-axis. However, this mode profile cannot be replicated exactly in the waveguide due to its boundary conditions. The exact beam size of the THz pulse is not fixed, and so the two coupler designs in Figs. 4 and 5 were individually optimised to maximise transmission of the input mode to the LSM_{11} mode of the DLW operating at $v_p = c$. The parameters are shown in Table 2. These modes are closely matched to a free-space THz mode created by two separate nonlinear crystals. The s_{21} parameter for the input mode to the LSM_{11} mode is shown in Fig. 8. Coupler B is preferable for maximal transmission to the correct mode. Additionally there is minimal transmission to higher order accelerating modes.

Table 2: Optimised Coupler Parameters

	Coupler A	Coupler B
Coupler length	4000 µm	6000 µm
Dielectric slab separation	200 µm	200 µm
Width	725 µm	600 µm
Dielectric slab thickness	300 µm	300 µm

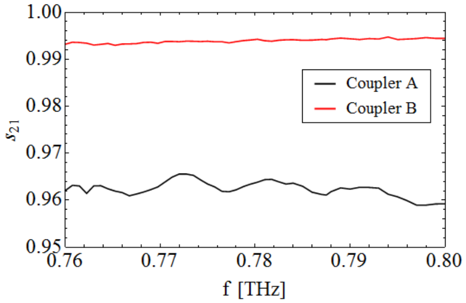

Figure 8: s_{21} parameter for Coupler A and Coupler B of the input mode to the LSM_{11} mode.

CONCLUSIONS

A waveguide and coupler have been designed for a THz-driven electron acceleration experiment. Final structure parameters are subject to changes with the THz source. Future work includes testing of the coupler without the electron beam, before beam testing takes place on the Versatile Electron Linear Accelerator (VELA) at Daresbury Laboratory.

REFERENCES

[1] R. J. England *et al.*, "Dielectric laser accelerators", *Rev. Mod. Phys.*, vol. 86, p.1337, 2014

[2] L. Xiao *et al.*, "Field analysis of a dielectric-loaded rectangular waveguide accelerating structure", *Phys Rev. E*, vol. 65 p.016505, 2001

[3] P. Schoessow *et al.*, "CVD diamond dielectric accelerating structures", *AIP Conf. Proc.*, vol. 1086, 2009

[4] R. E. Collin, *Field Theory of Guided Waves*, 2nd edition: Oxford University Press, 1991

[5] R. G. Hunsperger, *Integrated Optics: Theory and Technology*, 6th edition, Springer, New York, 2009

[6] M. J. Cliffe *et al.*, "Longitudinally polarised single-cycle terahertz pulses generated with high electric field strengths", *Appl. Phys. Lett.* vol. 108, p.221101, 2016