ISBN: 978-3-95450-194-6 ISSN: 2226-0366 doi:10.18429/JACoW-LINAC2018-THPO016

INVESTIGATION OF 2D PBG-WAVEGUIDES FOR THz DRIVEN ACCELERATION

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Abstract

There is significant interest in novel accelerating techniques which can overcome the limitations of conventional radio-frequency (RF) based devices in terms of frequency, gradient, and footprint. Moving from the RF to the terahertz (THz) frequency range, higher accelerating-gradient of high-energy beams can be achieved, as well as structure miniaturisation. Furthermore, in respect to the optical frequency range, THz allows for larger structures and better beam quality. This work has been investigating the use of a 2D photonic-bandgap dielectric waveguide (PBG-W) for THz-driven electron acceleration which could potentially offer a good compromise between dispersion engineering, low losses and ease of parallel illumination. Dispersion characteristics of the accelerating mode are studied to achieve the best compromise between high accelerating field and effective accelerating bandwidth, assuming a ~10% bandwidth of the THz driving pulse.

INTRODUCTION

With current state-of-the-art particle accelerators reaching several kilometres in size, a paradigm shift is required for future technologies to prevent them becoming unattainable. Terahertz (THz) frequencies offer the opportunity to build micron-scale structures, and the use of dielectrics over metal offers the ability to push fields higher due to the increased breakdown resistance—or fluence threshold. Additional benefits over optical frequencies, which similarly exhibit the prior stated benefits of THz, is the larger aperture sizes allowed for the beam and the higher bunch charges THz affords beams to use.

In conventional RF-driven accelerators, sources are typically narrowband—usually on the order of a few percent. In the regime of ultrashort THz pulse, broad bandwidths are generated and require a more careful study of the beam-pulse interaction. Much of the current work investigating THz acceleration has focused on the use of corrugated and dielectric-loaded waveguides (DLWs), of both rectangular and cylindrical geometry. While these devices are effective, they are hindered by the use of metal walls—which at THz frequencies exhibit large ohmic losses. [1] Due to the wavelength scales of THz, employing photonic-crystal (PhC) theory for confinement instead of metal walls can offer low ohmic losses and high fluence threshold. Moreover, the design flexibility offered by PhCs can potentially aid the tailoring of the accelerating mode dispersion for the THz acceleration regime.

For comparison with other designs such as the DLW proposed in [2] and ease of realisation, a rectangular waveguide configuration is chosen. This work focuses on waveguides based on a 2D-PBG slab structure with a triangular lattice of air/vacuum holes, offering a good compromise between design flexibility and ease-of-manufacture.

PBG-WAVEGUIDE DESIGN

Using MPB [3], initial 2D simulations of the PhC unit cell were carried out to optimise the fill factor of the PBG structure for maximum bandgap around the central frequency of 1 THz. The dielectric material used was silicon with relative permittivity $\varepsilon_r \sim 11.6$. The maximum photonic bandgap (PBG) was found to be at a radius of $r = 0.445a$ yielding a bandgap of 50% in the normalised frequency region of 0.29-0.48 $\omega a/2\pi c$, where ω is the angular frequency, a is the PhC period, and c is the speed of light. The schematic of the proposed PBG-waveguide is shown in Fig. 1.

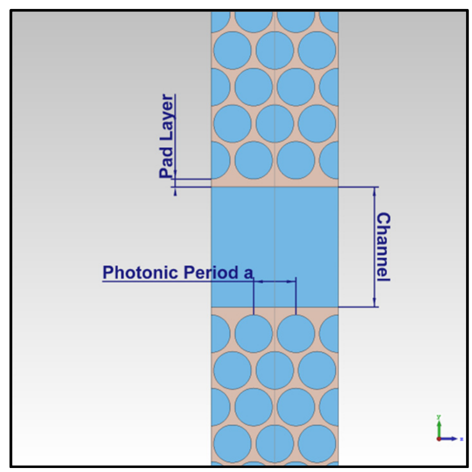

Figure 1: Schematic of three longitudinal unit cells of the PBG-W, with z-axis being direction of propagation.

The PBG-W is then realised by introducing a line defect along the longitudinal direction z across the PhC lattice for confinement of specific electromagnetic states (as propagating modes) within the PBG. In the case of DLWs, the modes can be described as a superposition of both TE and TM modes as the longitudinal-section magnetic (LSM) mode if either x or y components of the magnetic fields is set to 0, likewise longitudinal-section electric (LSE) if one of the transverse electric fields is set to 0 [4].

PBG-Ws such as shown in Fig. 1 are both nonhomogeneous and anisotropic—as such, they cannot support true LSE/LSM modes. At lower wavenumbers however, these modes serve as a good approximation for the PBG-W modes. Higher wavenumbers often exhibit higher levels of coupling to the dielectric over the waveguide channel which modifies the dispersion curve.

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To design the PBG-W, initially 2D models were investigated where the channel width and *pad layer* thickness (Fig. 1) were varied based on the work by Cowan [5]; allowing for a suitable dispersion of the accelerating mode at the point of interaction with $v_p = c$ and f=1 THz to be found at channel width ~ $3a$ and pad-layer ~ $0.1a$. This provided a starting point for the design of the 3D waveguide and its optimisation for highly-relativistic THz acceleration.

A 3D PBG-W was then designed considering a finite thickness of the dielectric slabs bound with metal. It was found that the accelerating mode tends infinitely to zero at the metal walls, so lower losses are expected than in a metal waveguide structure. The thickness of the PBG-W and the channel width were then investigated to study optimisation of the structure-particle beam interaction for broadband pulse excitation by comparing characteristic impedance and accelerating bandwidth.

Characteristic Impedance

One of the main figures of merit (FoM) in conventional RF accelerators is the shunt impedance r_s. The difficulty in applying this to PhCs however is the calculation of the wall dissipation that is not trivial. The characteristic impedance Z_c is typically used in the context of dielectric laser accelerators [1]. This is defined as the product of the accelerating field E_{acc} and wavelength λ with the Poynting vector along the axis of acceleration in the structure S via equation 1.

$$Z_c = \frac{(E_{acc}\lambda)^2}{S} \tag{1}$$

CST Microwave Studio® Eigenmode solver was used to investigate the effects of channel size on the metal bounded PBG-W at the point of beam-wave interaction in structures with a=117 µm, hole radius $0.445a$, and pad layer of 13 µm. Z_c was calculated for PBG-Ws ranging in thickness from 283-425 µm and channel width 266-398 µm. The effects of these two parameters on the characteristic impedance can be seen in Fig. 2, with the centre point taken at the original dimensions chosen. While there exist higher interaction points on the map, these are coupled with a low group velocity which made those points less desirable for THz acceleration due to shorter interaction times between the pulse and bunch.

Dispersion Control

While Z_c can be calculated from a single eigenmode simulation at the point of interaction providing a good FoM for comparison, due to the broadband nature of THz the efficient design of interaction within the PBG-W requires full spectral pulse-beam analysis. One key property to investigate this in the accelerating mode is its dispersion as this conveys information on the acceleration bandwidth, and the phase/group velocities of the EM fields. A comparison of the accelerating mode dispersion of the DLW based on [2] with dielectric layers on the top and bottom at 10% waveguide thickness per layer and the PBG-W with dimensions corresponding to the centre-point of Fig. 2 is shown in Fig. 3.

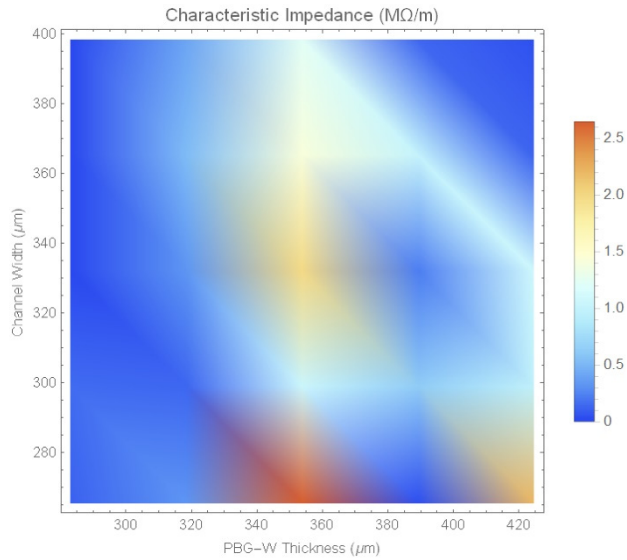

Figure 2: Variation of characteristic impedance with PBG-W thickness and channel width.

Accelerating Bandwidth

When the dispersion of a mode is known, the phase-synchronicity with a particle beam for each frequency is also revealed. In a structure of length L, a certain number of frequencies will propagate with a positive accelerating effect. The Fourier analysis of this acceleration can be calculated via equation 2.

$$VT(\omega) = \int_0^L E_0 \exp\left[iz\left(k_z - \frac{\omega}{c}\right)\right] dz \tag{2}$$

Where E_0 is the electric field at each frequency and k_z is the longitudinal wavenumber. In a structure of 5 mm length, the Fourier series for the PBG-W was calculated.

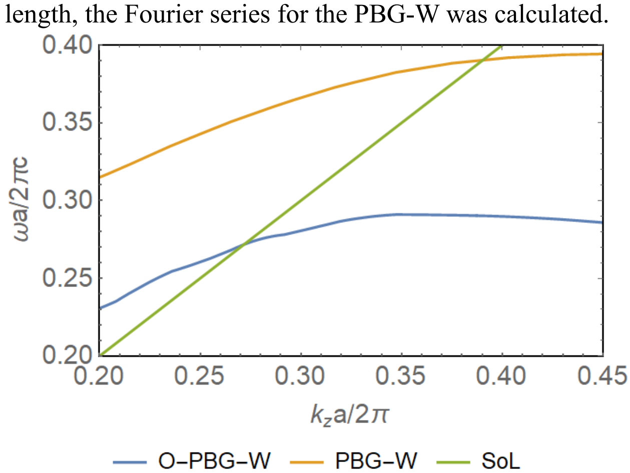

Figure 3: Dispersion of accelerating mode for the PBG-W, the O-PBG-W, and their interaction with the $v_p = c$ line (SoL).

While this information is useful, with the peak showing the likely ideal centre frequency for acceleration, it doesn't give a true picture of what a particle will see

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when being accelerated. Taking the peak as the centre-frequency and integrating in steps of increasing bandwidth around this point gives a plot of the total voltage seen by a beam when a pulse of a given bandwidth is injected as in equation 3.

$$VT = \int_{\omega_1}^{\omega_2} \frac{VT(\omega)d\omega}{\omega_2 - \omega_1} \tag{3}$$

It can be seen from the blue curve in Fig. 5 that although the accelerating voltage starts high, it rapidly drops off negligible levels by ~13% BW. In broadband pulse driven accelerators, this is not ideal behaviour.

Structure Optimisation for THz Pulses

It can be seen from Fig. 4 that the PBG-W needs to be optimised to better take advantage of the bandwidth of the driving pulses which are typically short at this frequency. Part of this problem is due to matching a broadband pulse with the interaction being near the peak of the dispersion curve thus nearly half of the injected pulse will be wasted and evanescently decay from the injection site or couple to spurious modes. To optimise the structure for this spectral distribution of the driving pulse, the structure was redesigned to operate at a lower point on the dispersion curve. While a hole radius of 0.35a offers a PBG of 41% unlike the 50% PBG available at 0.445a, it still encompassed the dispersion of the accelerating mode at the frequencies of interest. It has the additional benefit of operating in a region with higher group velocity thus contributing positively towards the R/Q of the accelerating structure.

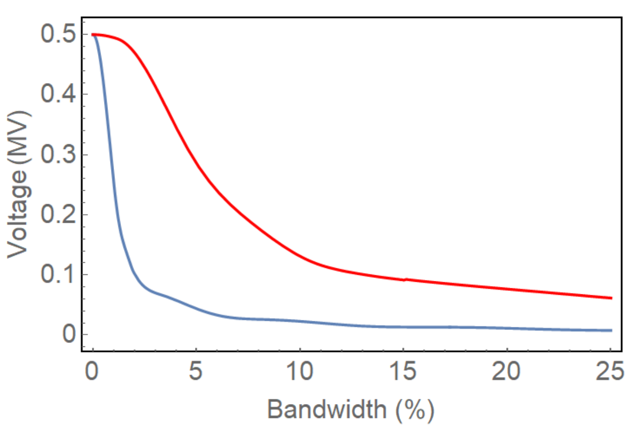

Figure 4: Integrated accelerating voltage for PBG-W (blue), and O-PBG-W (red), both calculated using $E_0 = 100\ MV/m$ across all frequencies.

An optimal geometry was found by introducing the additional parameter of a metal wall dielectric padding layer where both the group velocity and interaction yield better results than the original structure. The parameters for this optimised structure (O-PBG-W) can be seen in Table 1 with dispersion of the accelerating mode compared to the PBG-W and DLW in Fig. 3. Variation of accelerating voltage with pulse bandwidth is shown as the red curve in Fig. 4; it can be noted that a higher total accelerating voltage is realised across the entire bandwidth range.

Table 1: Parameters and FoMs for Optimised PBG-W

Parameter	Value	Unit
PhC Period (a)	82	µm
Hole Radius r/a	0.35	
PBG-W Channel Width	401	µm
PBG-W Thickness	454	µm
PhC Pad Layer	16	µm
Wall Pad Layer	23	µm
Waveguide Length	5.0	mm
Group Velocity	0.24c	
Phase Velocity	1.00c	
Characteristic Impedance	10.51	MΩ/m
R/Q	0.11	MΩ/m

CONCLUSION

The design of a photonic-crystal based waveguide to accelerate highly-relativistic electrons driven by THz radiation has been investigated. It was shown that the photonic bandgap, accelerating mode dispersion and the synchronism point with the beam need to be carefully designed to satisfy the requirements in terms of accelerating bandwidth and characteristic impedance for THz-driven structures. Optimisation of the proposed PBG-W for broad bandwidths has resulted in a 6.5x improvement of accelerating voltage at 10 % bandwidth, and nontrivial accelerating voltages above 13% bandwidth with further optimisation of the structure is expected to improve this figure further. Comparison with other accelerating structures is required to truly quantify the accelerating properties of PBG-W and will be undertaken during further optimisation.

ACKNOWLEDGEMENTS

This work was funded by the Cockcroft Studentship grant. The authors would also like to thank the Institute of Physics and the LINAC Student Grant for their generous contributions towards facilitating attendance at the LINAC 2018 conference.

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