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WAKEFIELD EXCITATION VIA A METASURFACE-LOADED WAVEGUIDE *

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Abstract

A metallic waveguide loaded with layers of complementary split ring resonator (CSRR) based metasurface is presented for accelerator and coherent source applications. This structure presents left handed behaviour arising from the strong electrical response of CSRRs which form the metasurface and the transverse field confined between the closely positioned metasurface layers. The loaded waveguide structure is known to have a TM-like mode at 5.47 GHz suitable for acceleration. In this paper, the results of wakefield simulations are presented and a narrow band excitation identified around the frequency of the TM-like mode, indicating strong coupling between the beam and the field of this mode.

INTRODUCTION

Metamaterials (MTMs) are materials comprising of a periodic arrangement of subwavelength inclusions that give rise to electromagnetic effects not commonly found in nature. The most notable of MTM properties is the formation of a negative index media in which the permittivity ϵ and the permeability μ are simultaneously negative [1], these are often referred to as left handed media (LHM) [2]. In a left handed media the wave vector and Poynting vector propagate antiparallel leading to the phase and group velocity propagating in opposite directions. This left handed behaviour leads to backward propagation of phenomena commonly associated with electromagnetic waves, in particular the backward propagation of Cherenkov radiation.

The incorporation of MTMs and MTM elements into accelerators is a recently expanding field. The most prominent applications of MTMs within accelerators utilises the property of backward propagating Cherenkov radiation for numerous applications such as a coherent radiation sources, Cherenkov masers [3], and the development of Cherenkov wakefield detectors based on the MTM-loaded waveguides [4]. Backward propagating Cherenkov radiation has been verified in 2008 using a SRR and wire loaded waveguide [5] and in 2009 using a phased electromagnetic dipole array to mimic the propagation of a particle [6]. The use of MTM elements for deflecting [7] and accelerating [8] RF structures has been recently presented by I. McGregor et al. at the Cockcroft institute. CSRR based infinite metasurface waveguide structures without metallic walls have been theoretically discussed and simulated at MIT for coherent source and accelerator applications [9].

We propose a finite bounded form of this structure, the metasurface sheets have been loaded into a metallic WR-284 waveguide, with the layers lying parallel to the propagating electron beam. The results of wakefield simulations performed using the wakefield solver of CST Particle Studio [10] are presented and the coupling between the beam and the electric field is discussed.

METASURFACE WAVEGUIDE

The proposed metasurface-loaded waveguide is shown in Fig. 1, it comprises of four layers of CSRR-metasurface loaded into a metallic waveguide, with dimensions 72 mm by 34 mm (WR-284). The spacing between the layers is set at 6.76 mm, which is sufficient for a particle beam to propagate without the metasurface layers obstructing the beam causing radiation or disruption.

The period of the CSRR-metasurface, b, is 8 mm, the outer ring is $o = 6.6$ mm, the inner ring is $i = 4.6$ mm, the ring width is $w = 0.8$ mm and the gap width is $g = 0.3$ mm, as shown in the inset in Fig. 1. The gaps in the rings lie in the direction of beam propagation. For the simulations this waveguide has been truncated in the direction of propagation (z) to a length of 0.8 m, making the structure 100 resonators long and thus considered to be a bulk material.

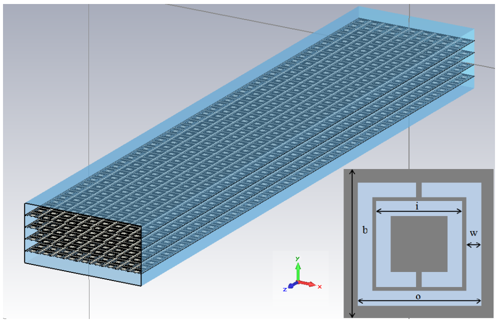

Figure 1: Schematic geometry of the metasurface-loaded waveguide. Inset shows the unit cell of the metasurface.

The waveguide acts as a LHM at certain frequencies as the resonant response of the CSRRs gives rise to negative permittivity and the transverse confinement of the modes between the MTM sheets leads to negative permeability. Through electromagnetic simulations using CST Microwave Studio, a left handed region has been identified with a TM-like operating mode identified at 5.47 GHz.

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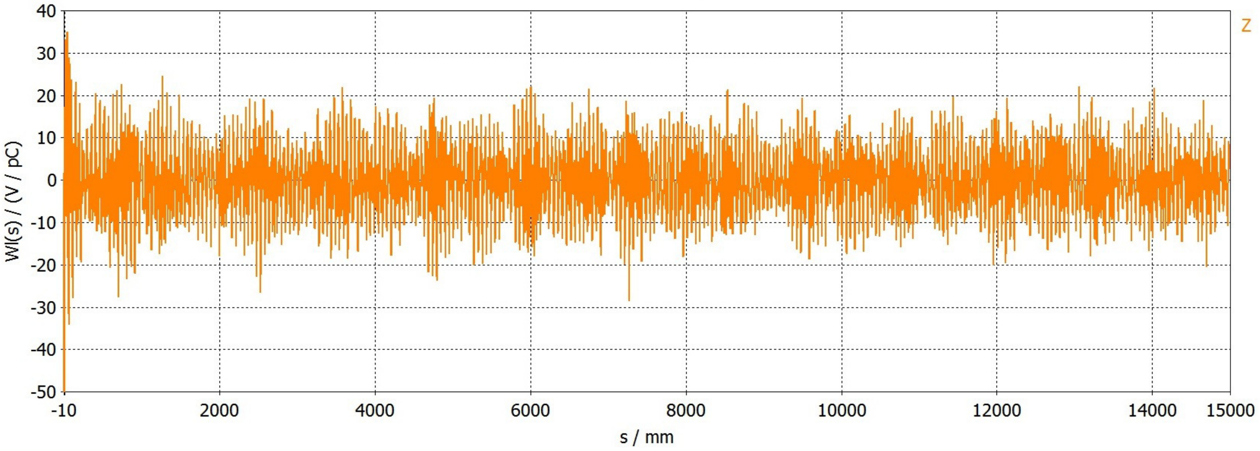

Figure 2: The longitudinal wake potential of the test bunch as a function of s the distance behind the impulse bunch.

This TM-like mode exhibits strong longitudinal electric field components in the region of beam propagation, making it suitable for applications in both accelerating and as a coherent source. This TM-like mode is surrounded by hybrid modes that exhibit some weak longitudinal field components distributed over the whole structure but cannot be considered suitable for acceleration. Through analytical analysis the TM-like mode was found to have high values of R/Q and shunt impedance compared to the surrounding modes, indicating good beam coupling, the results of the wakefield simulations will be utilised to verify this result.

WAKEFIELD SIMULATIONS

The wakefield solver in CST Particle studio has been used to simulate the transverse and longitudinal wakefields created by an electron bunch travelling through the structure. For the simulations the length of the test bunch is set to be significantly smaller than the wavelength of interest. The test bunch has σ =2 mm and a charge of 1 nC and is issued from a radial source with a radius of 2.5 mm located between the central layers. The wakefield solver cannot give a full characterization of the wave-beam interaction within the structure like the particle-in-cell (PIC) solver but provides an efficient method to estimate the coupling between the beam and the modes within the structure. Coupling between the beam and TM-like modes with strong longitudinal components is indicated by strong excitation in the longitudinal wake impedance.

The wake impedance $Z(\omega)$ is analysed to determine the existence of any excitation peaks. $Z(\omega)$ is a Fourier transform of the wake potential $W(s)$ divided by the charge distribution function $\lambda(s)$, as follows

$$Z(\omega) = -\frac{\int_{-\infty}^{\infty} W(s)e^{-i\omega s} ds}{\int_{-\infty}^{\infty} \lambda(s)e^{-i\omega s} ds} \tag{1}$$

Here s is the distance of the particle bunch behind the test bunch. Both the wake impedance and the wake potential have transverse and longitudinal components. It is the longitudinal component that will indicate the level of coupling between the beam and the TM-like modes within the structure. The longitudinal wake potential of our test bunch is shown in Fig. 2, the transverse wake potential is sufficiently small in comparison to not be shown.

The longitudinal wake impedance may be found from the longitudinal wake potential via (1) and is shown in Fig. 3. The particle bunch travelling through the MTM waveguide interacts with the TM-like modes, and produces a narrow band excitation in the longitudinal wake impedance, this corresponds to coupling between the mode and the beam at that frequency indicating its suitability for applications in acceleration and coherent sources. For our structure, narrowband excitation is observed at 5.8 GHz and can be seen in the inset to Fig. 3. The frequency of this excitation is in good agreement with the TM-like mode found via electromagnetic simulations, which exhibited strong longitudinal electric field on axis. Strong narrowband longitudinal wakes such as those shown in Fig. 3 are desirable as they indicate strong beam coupling and corroborate the results of analytical analysis and electromagnetic simulations. Conversely weak transverse wakes are required, as a strong transverse wake could disrupt the beam and reducing the efficiency of the structure.

In comparison to the longitudinal wake impedance there is very weak excitation of the transverse wake impedance in the y direction and virtually no excitation in x. A number of the transverse wake impedance excitations occur at the same frequency as the longitudinal excitations indicating the hybrid nature of the modes within this structure. The strongest excitation peaks of the y component of the transverse wake impedance is over two orders of magnitude less than the strongest excitation of the longitudinal response and thus will have minimal effect within the structure. Reduced transverse wakes are desirable, as a strong traverse wakes can destabilise the beam and lead to unwanted effects within the accelerating structure.

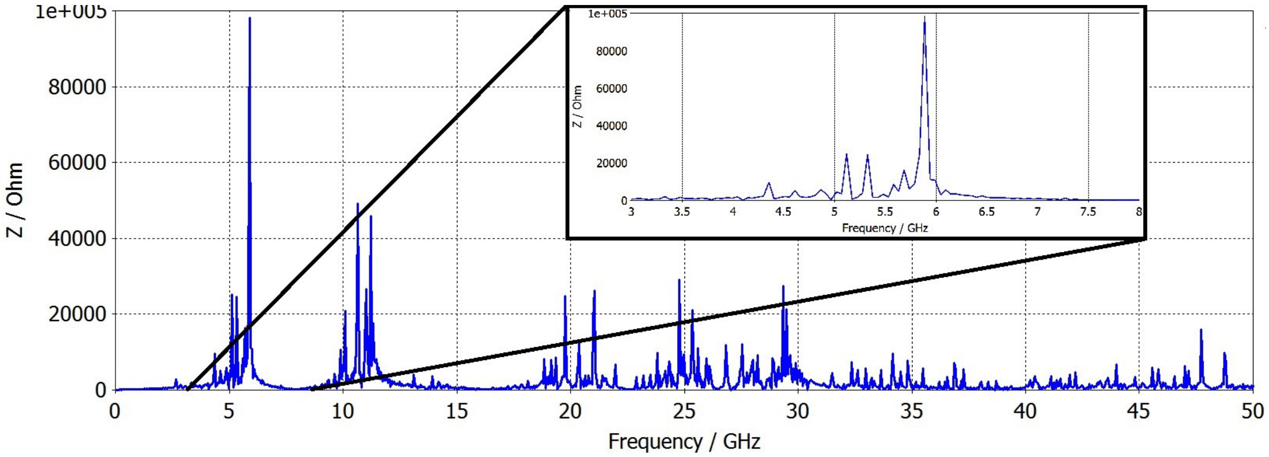

Figure 3: The longitudinal wake impedance showing a strong excitation corresponding to coupling with the TM-like mode. The magnitude of these excitations is much greater than those in the transverse directions.

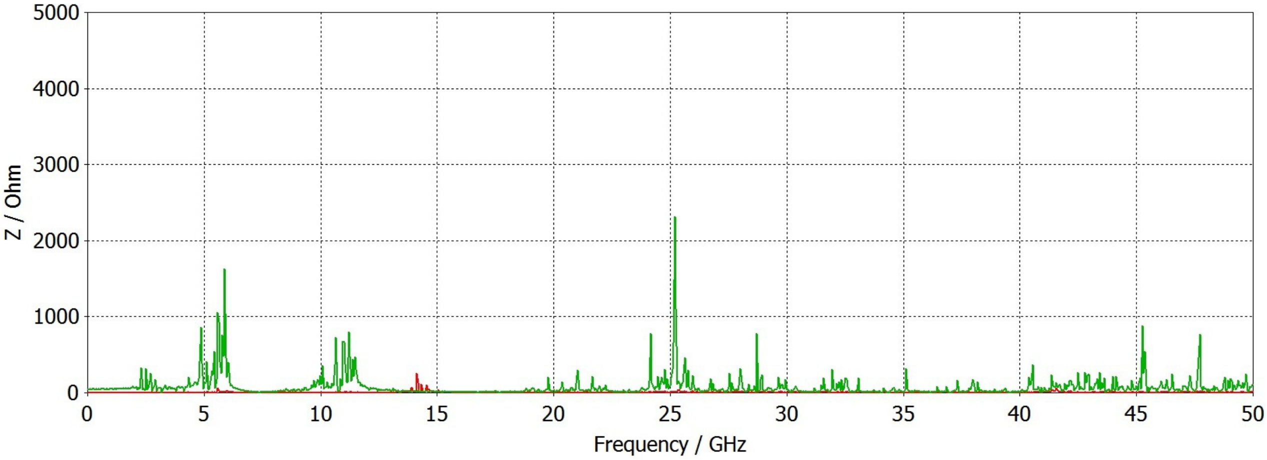

Figure 4: The transverse wake impedance of the structure showing the weak excitation of wakes in the *x* and *y* directions.

CONCLUSION

A metasurface-loaded metal waveguide is proposed for accelerating and diagnostic purposes. The structure exhibits a narrowband excitation of the longitudinal wake impedance at 5.8 GHz corresponding to strong coupling between the beam and the structure at this frequency. This excitation is in close agreement with the results from previous electromagnetic simulation which showed a TM-like mode occurring at 5.47 GHz. Considerably weaker excitations are observed for both transverse components of the wake impedance meaning there will be minimal disruption of the beam. Due to the nature of the CSSRs used within the structure, this loaded waveguide set up is scalable to alternative frequencies opening up applications as new forms of particle detectors or as a Cherenkov source.

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