Metamaterial Based Electromagnetic Sources

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Abstract

This project aims to establish the groundwork for a new class of compact, lightweight, high power, metamaterial based electromagnetic sources. Dispersion engineering along with novel properties displayed by metamaterials are utilized for the design and fabrication of a new class of microwave generation and amplification technologies. Beam-wave interaction facilitated by an artificial media producing 70 W power output has been demonstrated.

Finite Element Analysis

A two port network was set up using COMSOL Multiphysics (Figure 1). A single unit cell (Figure 2) comprising a Complementary Split Ring Resonator (CSRR) was placed between the ports. Behind each port scattering boundary conditions were applied preventing any reflections from propagating back into the system, periodic boundary conditions were also defined in both X and Y.

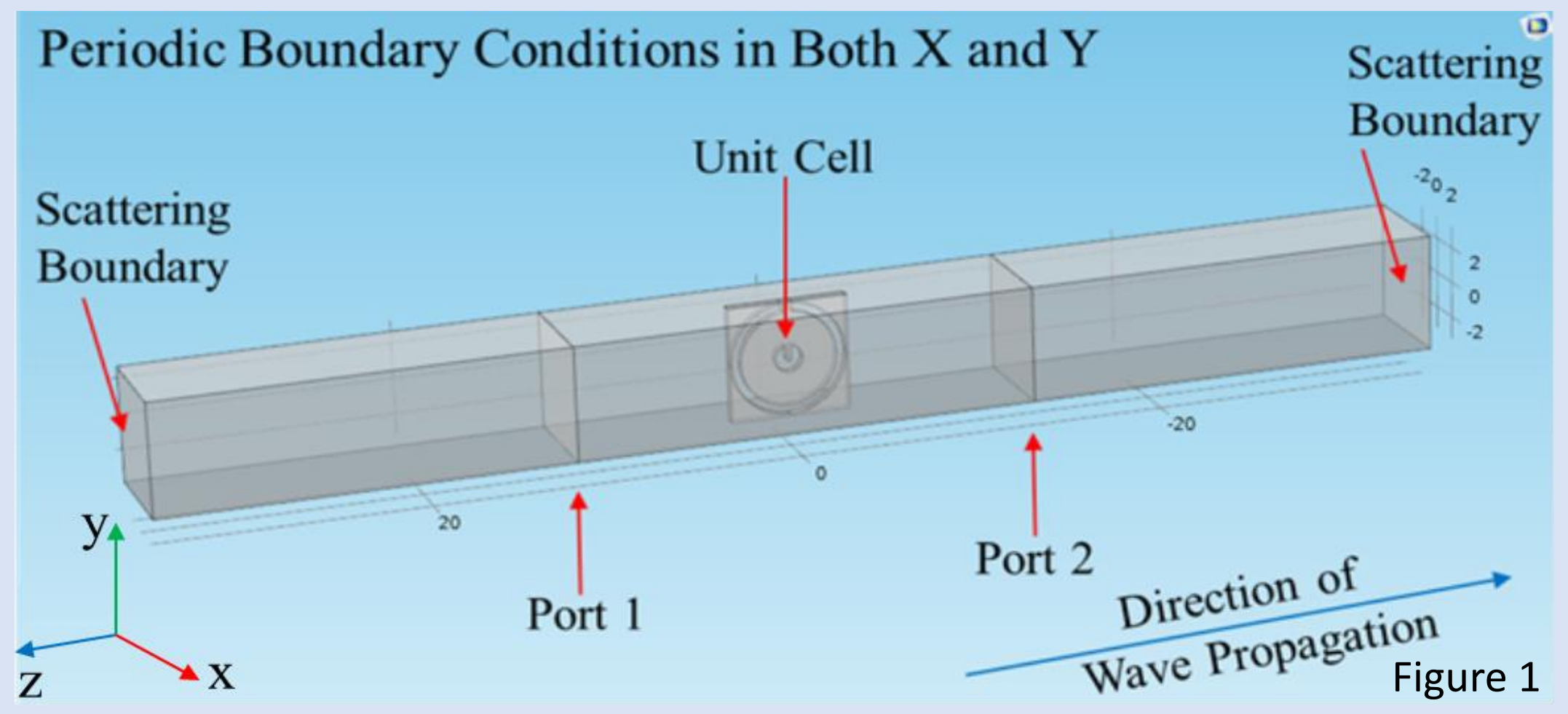

Figure 1

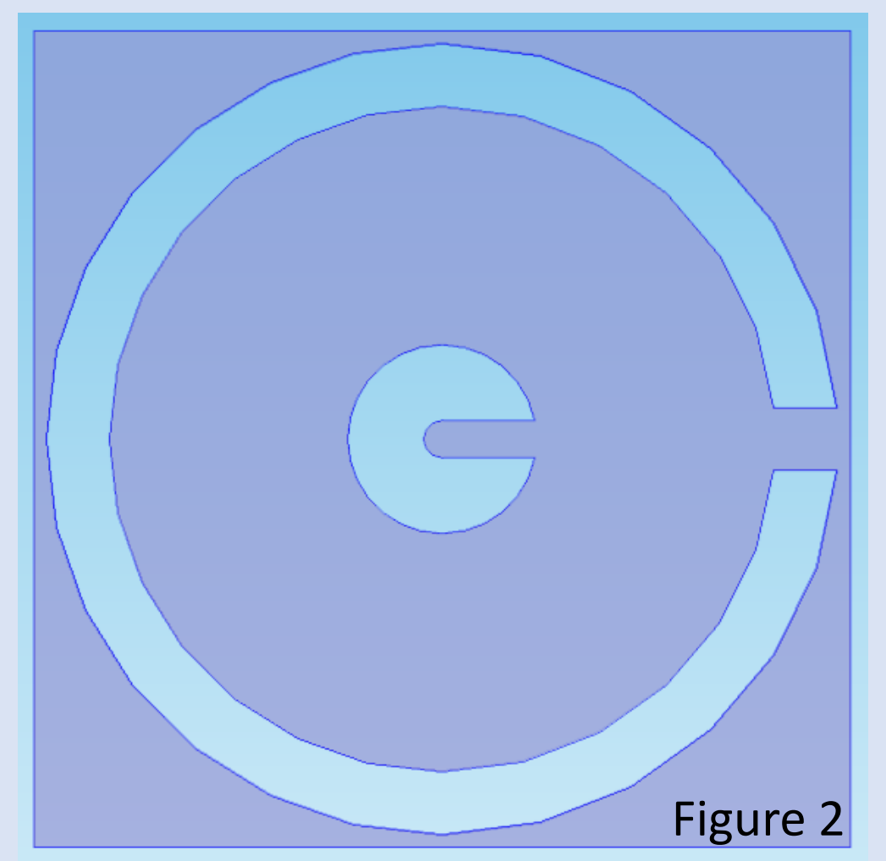

Figure 2

The complex S-Parameters obtained were processed using a MATLAB parameter extraction routine based upon a variation of the Nicolson-Ross [1] Wier [2] (NRW) approach adapted by Smith *et al* [3]. The impedance and refractive index were calculated allowing the effective permittivity (ε) and permeability (μ) of the artificial material to be determined. These parameters were then used to calculate the dispersion relation for the artificial material.

Effective Parameters

Figures 3 and 4 show the calculated values of ε, μ respectively. Figure 5 shows the refractive index (n) where Im (n) indicates low loss within the material at the frequencies of interaction.

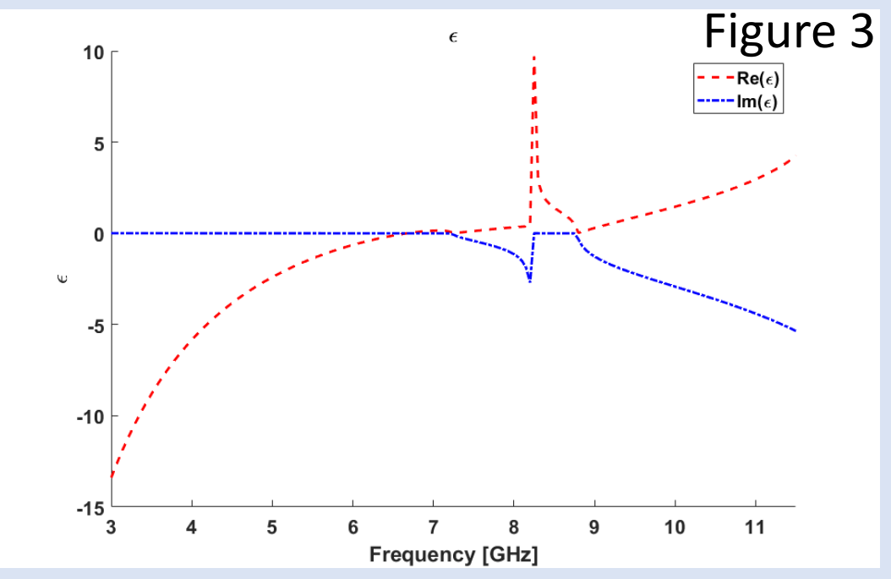

Figure 3

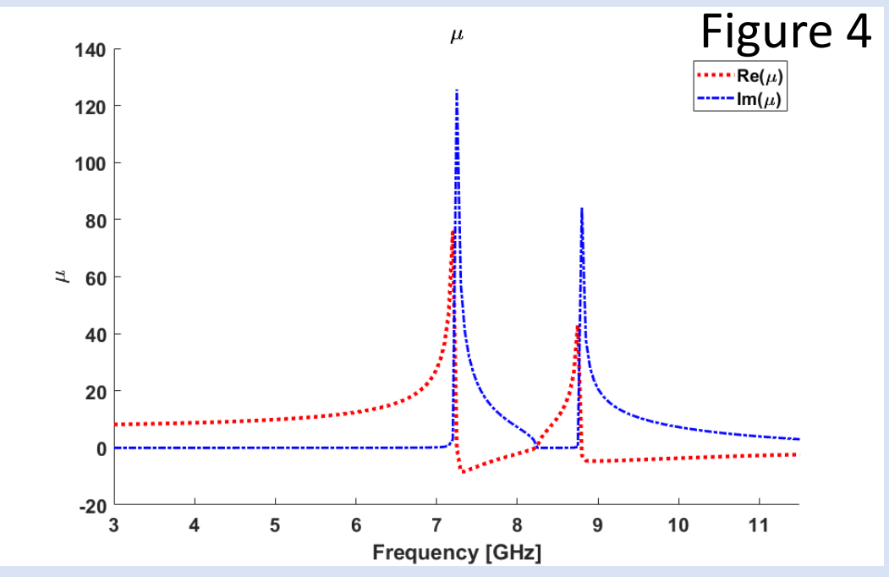

Figure 4

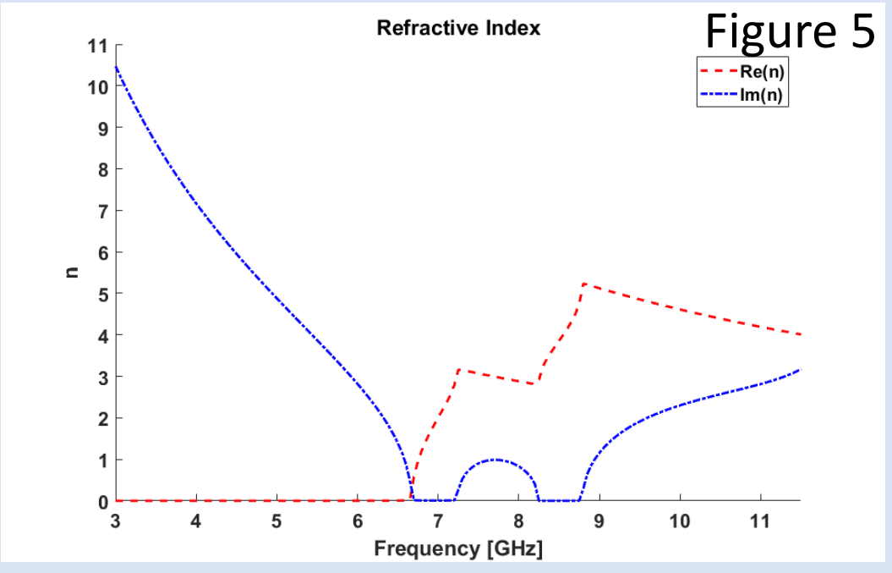

Figure 5

Eigenfrequency Analysis

Eigenfrequencies are discrete natural frequencies at which a system is inclined to vibrate as such a system will deform into a certain shape known as an eigenmode. Figure 6 Illustrates the COMSOL setup used for the analysis. The simulated domain consists of a cylindrical waveguide partially filled with the artificial media. The 'block' of material was defined using calculated effective parameters ε and μ .

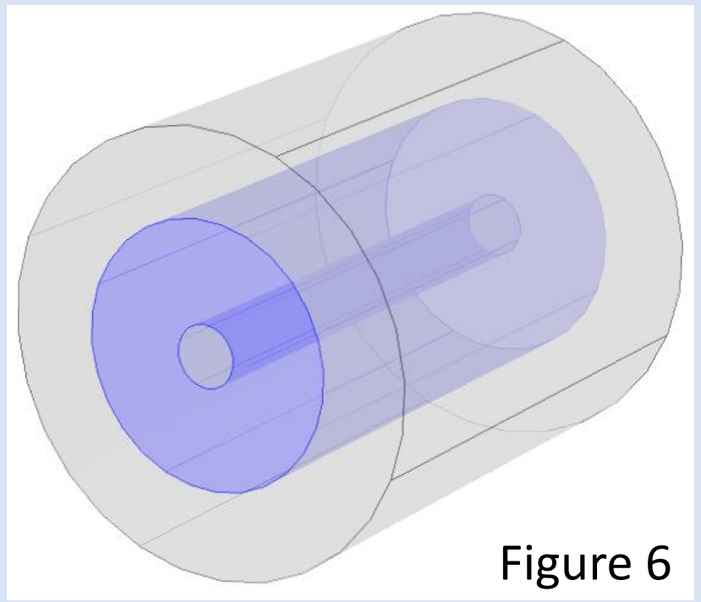

Figure 6

FDTD – PIC Simulations

For proof of principle two different simulations were initially carried out. The first modelled an empty rectangular waveguide with 2 output ports and a 20 keV electron beam was pulsed through the centre (Figure 7A). For the second simulation, the waveguide was loaded with four planar arrays of the CSRR unit cell. Each array was 3 unit cells by 5 (Figure 7B). The Fast Fourier Transform (FFT) calculated for both simulations were compared.

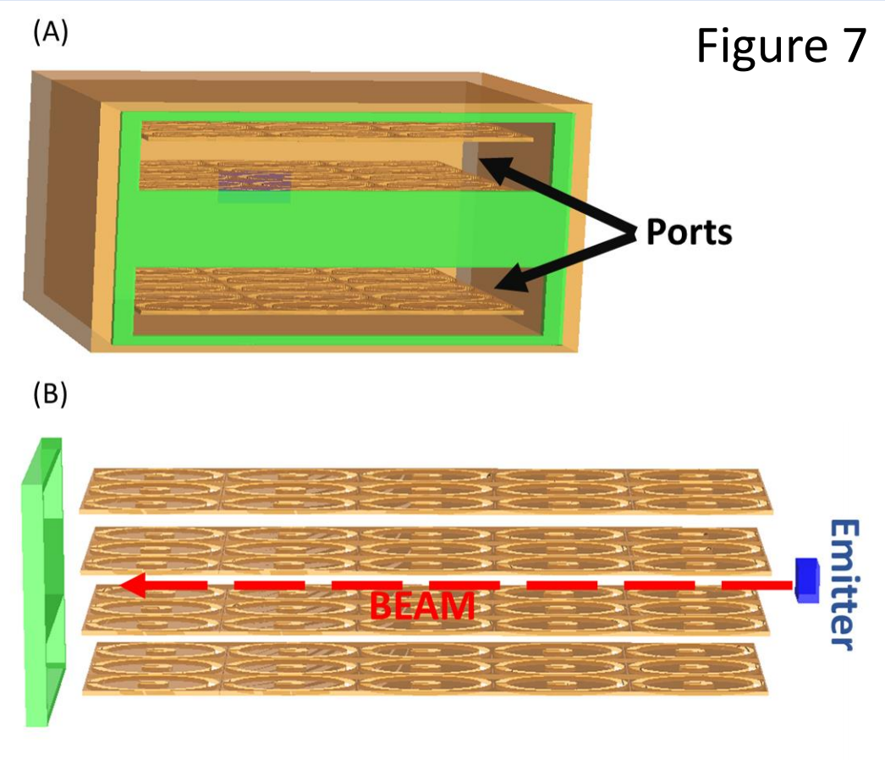

Figure 7

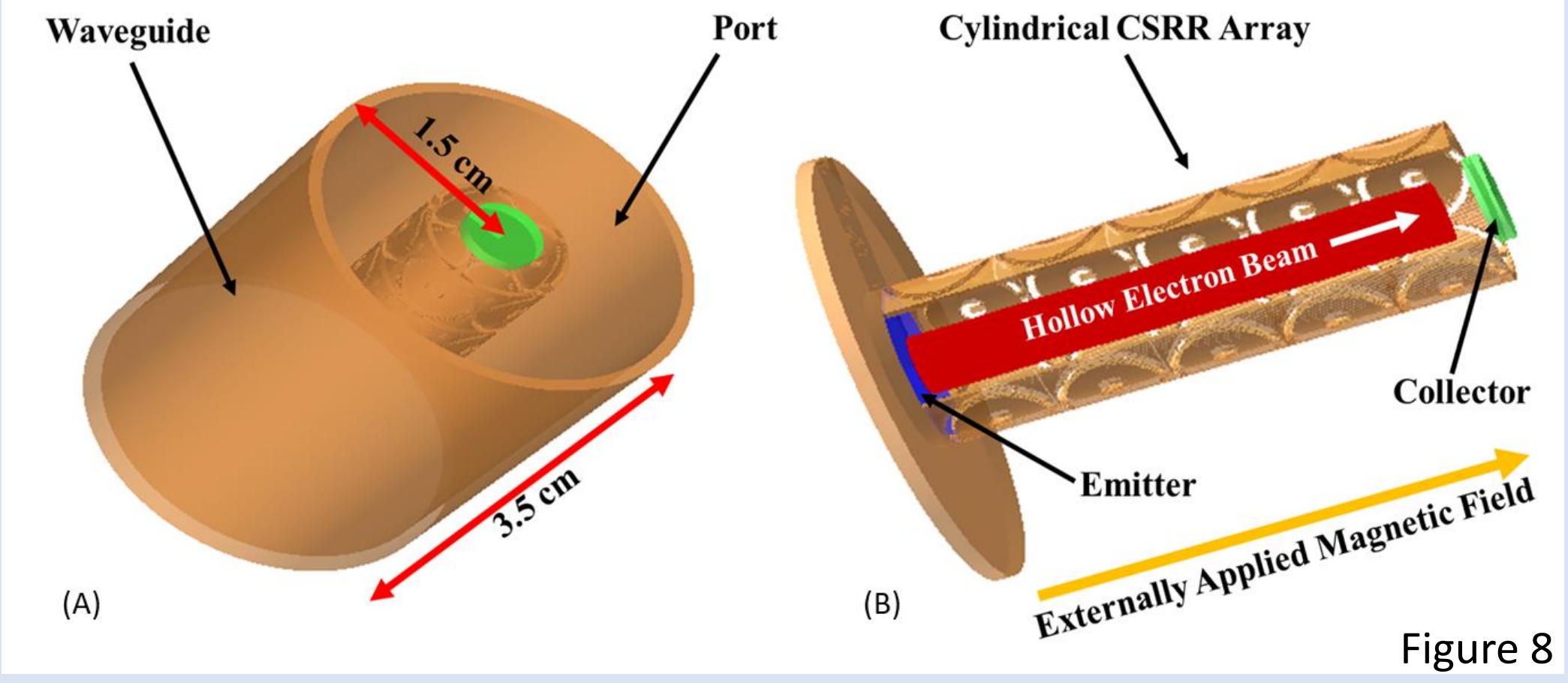

Figure 8

The current MAGIC setup is illustrated in Figure 8 where A shows the cylindrical waveguide loaded with a cylindrical array of the designed CSRR's and B illustrates the gyrating electron beam propagating on axis. The array is 5 unit cells in length by 5 unit cells around the circumference, has an internal radius of 14.18 mm and a thickness of 0.5 mm. An axial, static magnetic field of 0.315 Tesla is externally applied using pre-set commands within MAGIC.

Results

Figure 9 shows the dispersion relations calculated for the artificial material. When loaded into waveguide interaction with a 30 keV beam at 7.25 and 8.28 GHz and interaction with a 20 keV beam at 8.45 GHz was predicted. Figure 10 shows the FFT from the initial FDTD simulations for the empty and loaded systems. The empty waveguide FFT shows only low-level broadband noise. The FFT for the loaded system shows a clear peak around the interaction frequency indicated by the dispersion relation in Figure 9. COMSOL Multiphysics was used to determine the power handling capabilities of the artificial material. The steady state temperature was plotted vs power (Figure 11) to determine the power handling capability of the artificial media. The data suggests that the material can withstand power levels greater than 1 KW. Further FDTD simulations were conducted using a cylindrical CSRR array and waveguide with a 20 keV cyclotron electron beam propagating on axis. The power output from the modified system is shown in Figure 10. Currently a peak power of approximately 70 W has been achieved.

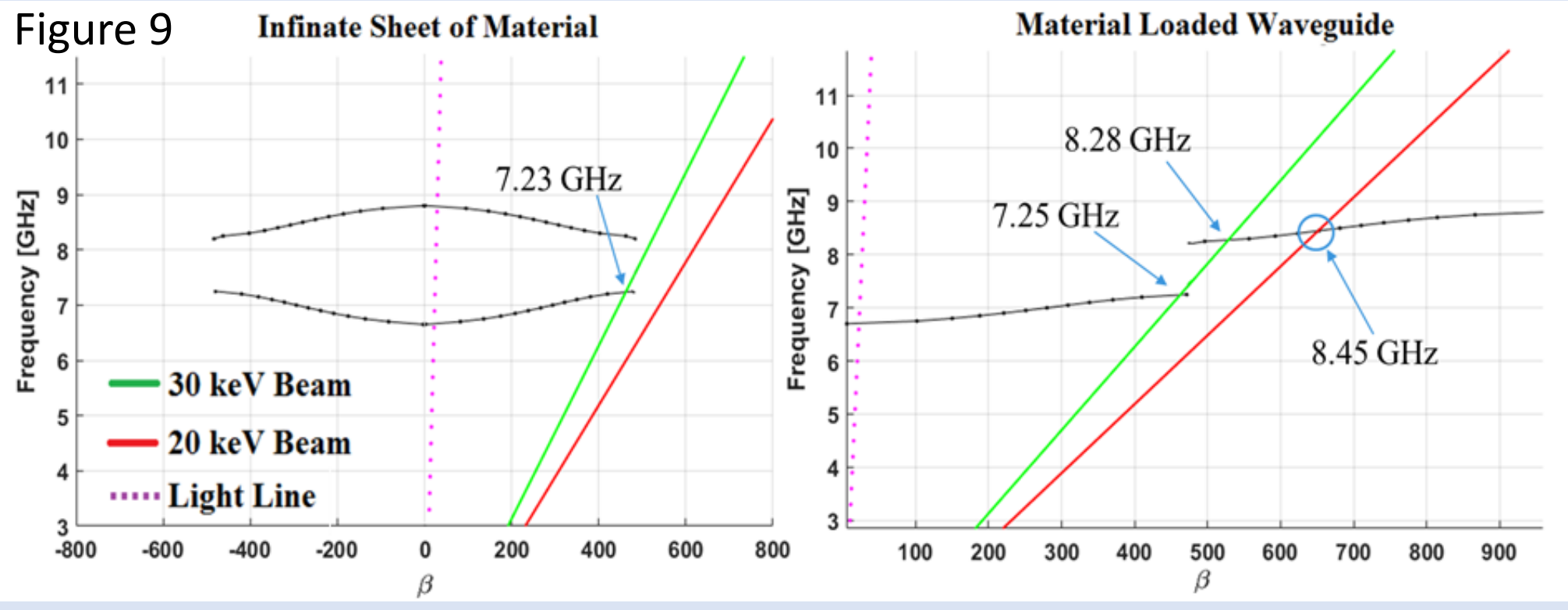

Figure 9

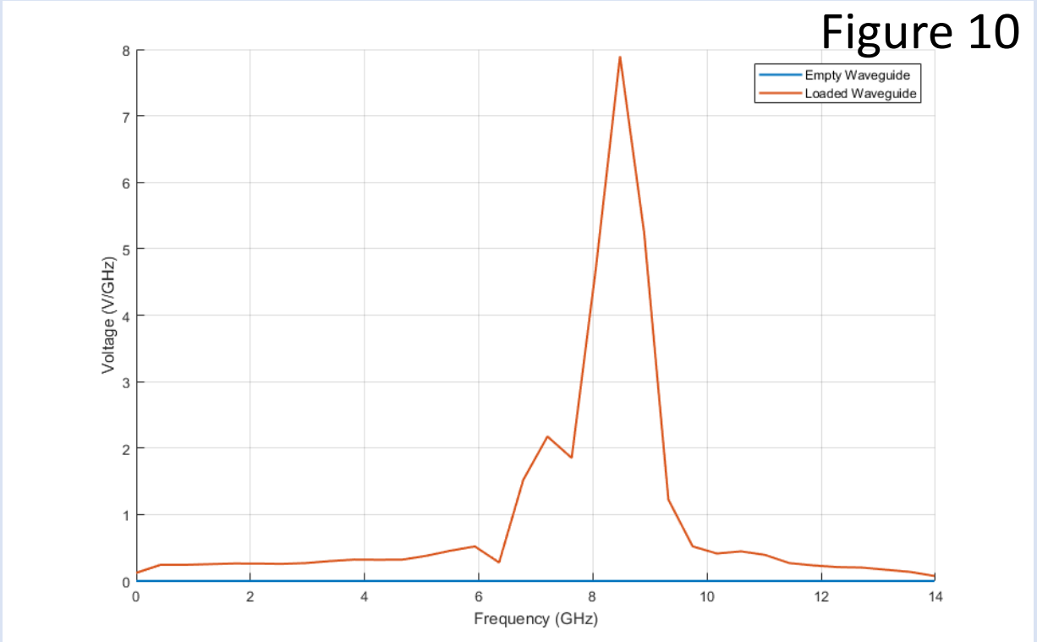

Figure 10

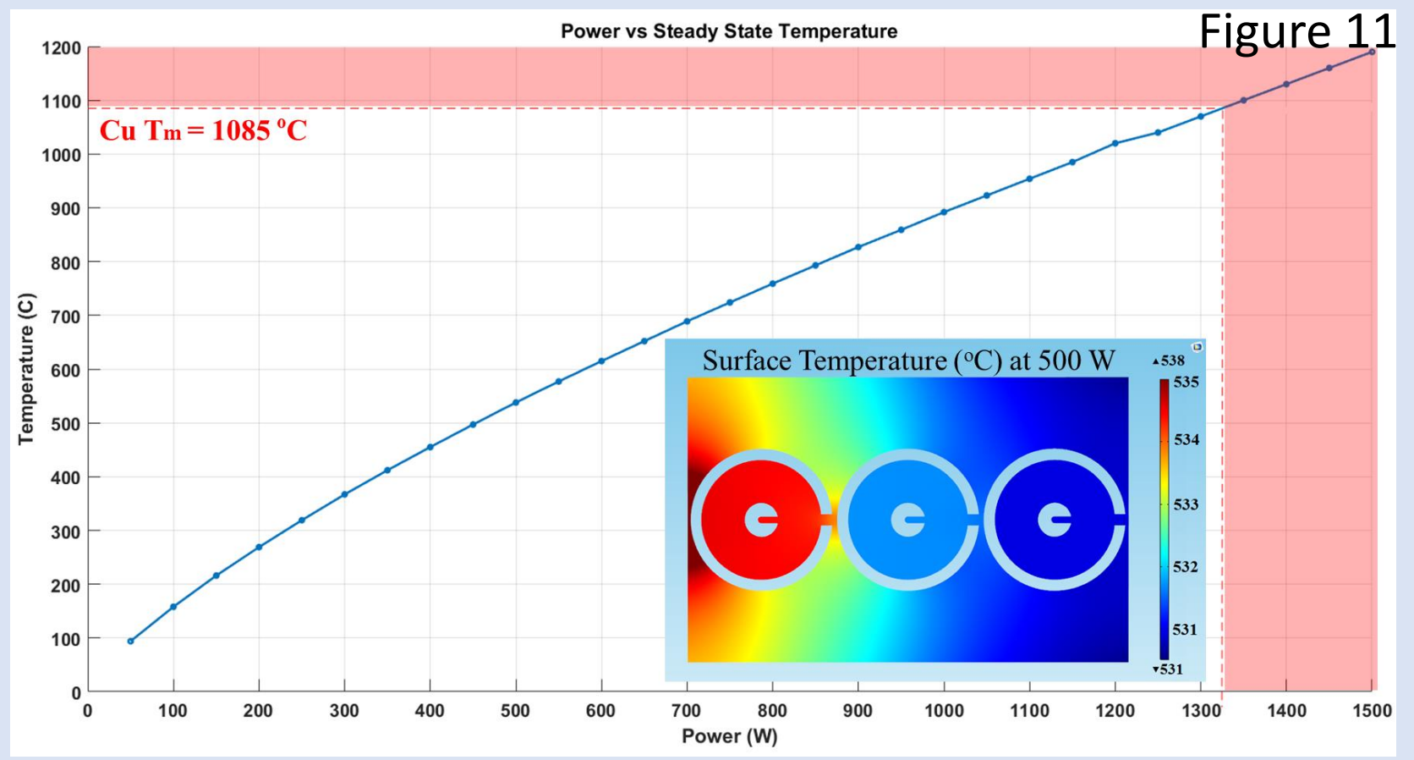

Figure 11

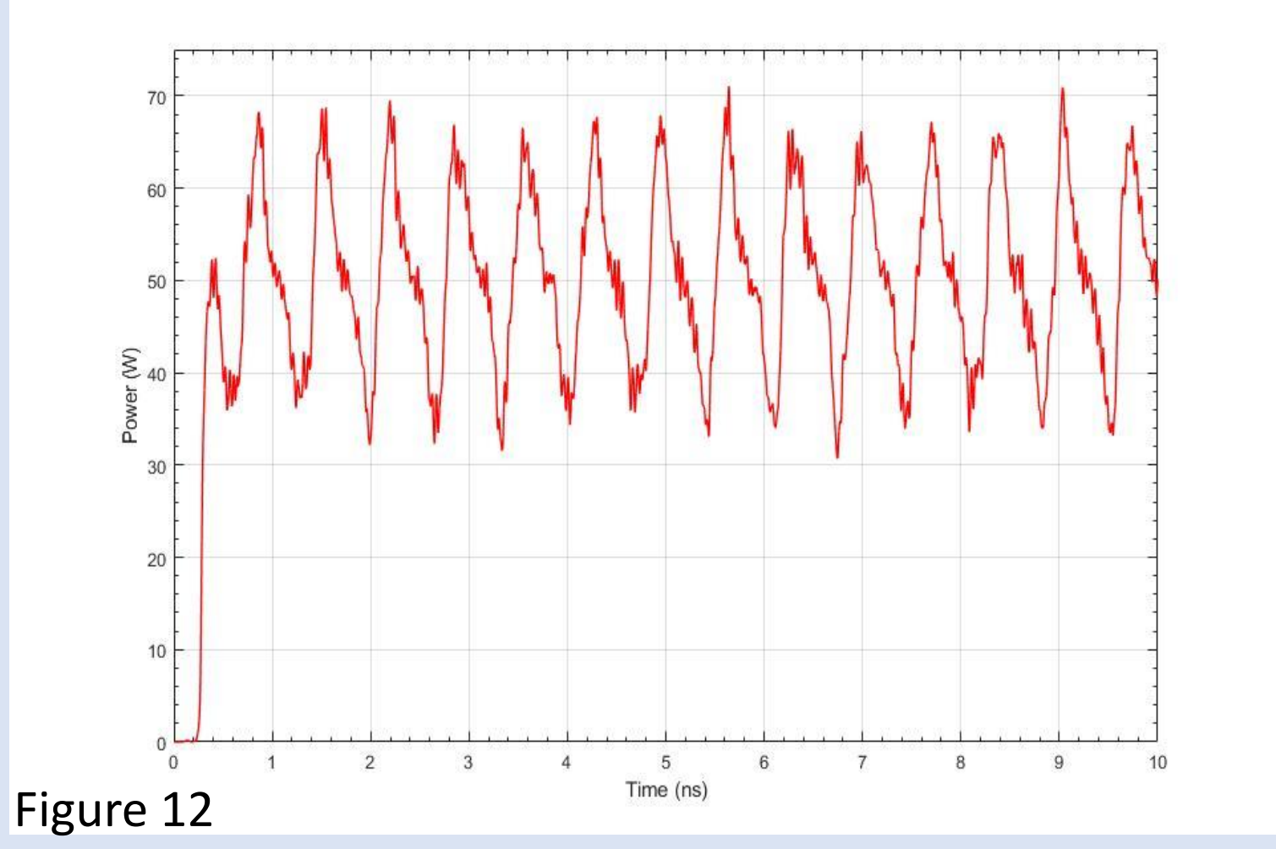

Figure 12

Discussion

The FFT from the current loaded cylindrical system is shown in Figure 13 along with the associated eigenmodes at each frequency. The eigenmodes were determined using COMSOL Multiphysics. The field patterns calculated correspond to those output by MAGIC. Figure 14 shows a comparison of field patterns produced by COMSOL and MAGIC

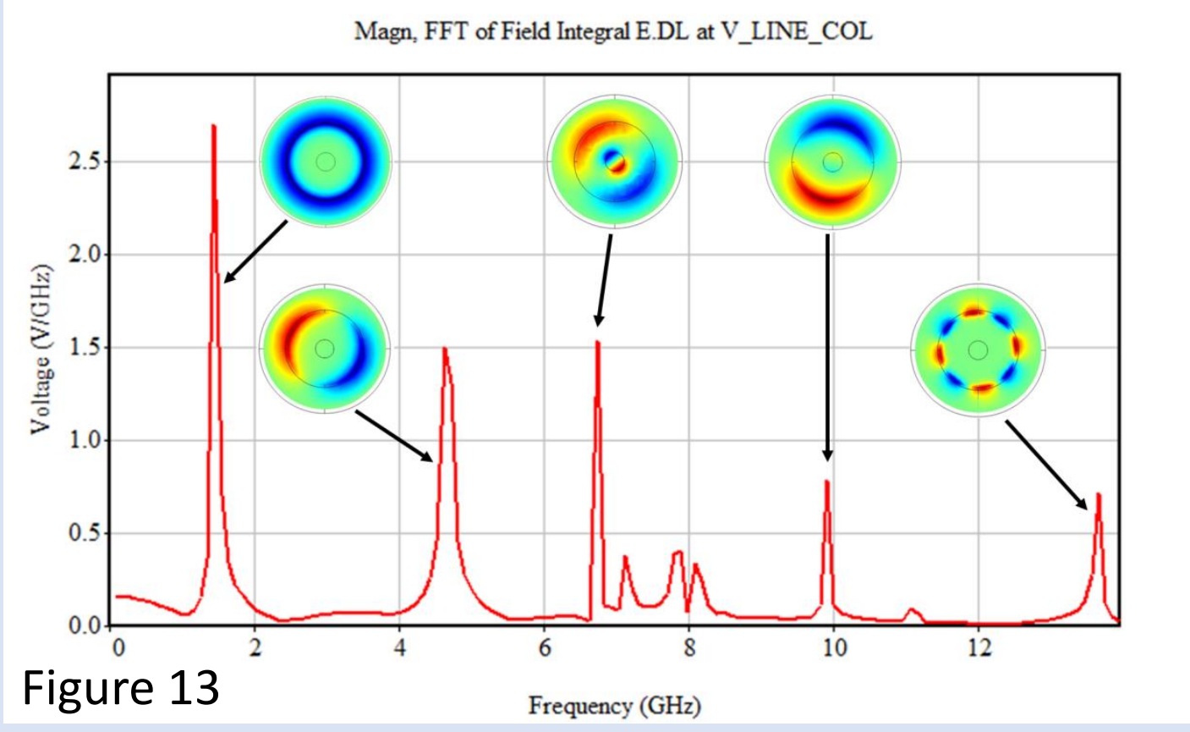

Figure 13

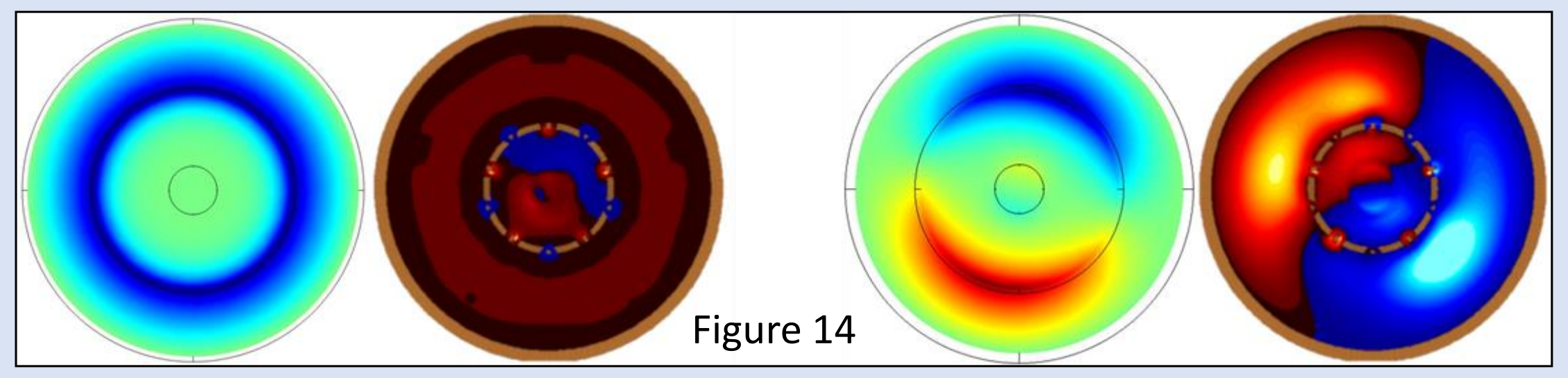

Figure 14

Summary

- A CSRR unit cell was designed producing a low-loss artificial material
- Novel beam-wave interaction and energy transfer demonstrated
- The effective parameters, ε and μ calculated via NRW method
- Dispersion characteristics of the material were determined
- Data suggests the material can withstand power levels greater than 1 KW
- A peak power of approximately 70 W has been achieved

Future Work

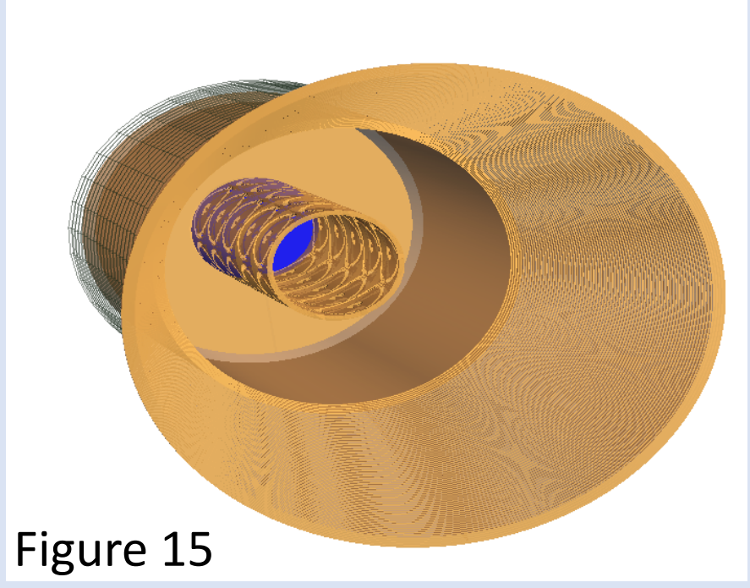

Figure 15

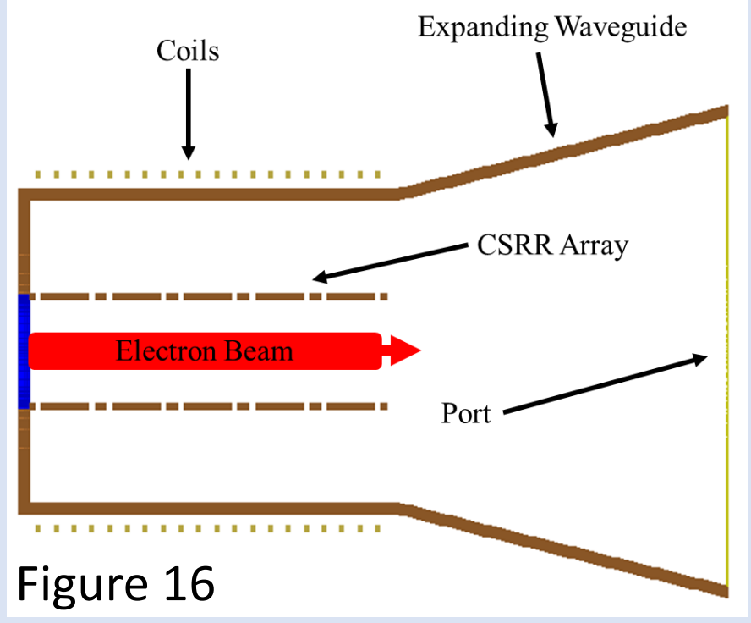

Figure 16

- Maximise the beam-wave interaction
- Determine and improve the efficiency
- Overcome issues with reflections
- Look into impedance matching
- Improve output coupling (Figures 15 and 16)
- Fabricate using precision engineering techniques
- Experimentally determine the response of the material
- Compare results obtained to the simulation data

References

[1] Nicolson, A.M and Ross, G.F. (1970). Measurement of the intrinsic properties of materials by time domain techniques. Trans. Instrum. Meas., 19 (4), 377-382.

[2] Wier, W.B. (1974). Automatic measurement of complex dielectric constant and permeability at microwave frequencies. Proc. IEEE, 62 (1), 33-36.

[3] Smith, D.R., Vier, D.C., Koschny, Th. and Soukoulis, C.M. (2005). Electromagnetic parameter retrieval from inhomogeneous metamaterials. Phys. Rev. E, 71 (036617).

Acknowledgements

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