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Numerical Analysis and Experimental Design of a 103 GHz Cherenkov Maser

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***Abstract*— Numerical FDTD and PiC simulations demonstrate the successful electron wave interaction in a Cherenkov maser utilizing a cylindrical 2D PSL as a mode selective cavity. Optimization of this structure's physical properties results in the design of a cavity with 16 longitudinal periods of 1.6 mm length, 7 azimuthal variations and an unperturbed inner radius of 4 mm. In numerical simulations this design produces an output power of 300 kW with 10 % efficiency at a frequency of 103.6 GHz.**

I. INTRODUCTION

MODE selection associated with periodic surface lattice (PSL) structures allows the formation of optimized cavity eigenmodes with physical parameters that can induce efficient electron-wave coupling in a variety of different coherent sources [1-4]. We present the design of the experimental set-up to study a W-band 2D Periodic Surface Lattice (PSL) of cylindrical topology.

In the present case coherent electron emission is achieved in an over-moded structure by way of an azimuthally symmetric volume field (VF) which couples with a transversely evanescent surface field (SF) to form an eigenmode, the eigenmode will have an E_z component that interacts with the axial velocity of the electrons via the Cherenkov instability. The goal of the present research is the observation of coherent high-power (HP) Cherenkov radiation from an oversized annular electron beam interacting with an azimuthally symmetric TM_{0n} near cut-off mode coupled to the $HE_{m,n}$ SF that has the highest Q value as compared to other competing modes. This mode selection process creates an initial timespan for the production of the dominant cavity eigenmode and does not preclude the existence of, and the interaction with, other parasitic modes with lower radial indices, however, the tailoring of the physical parameters of the PSL can minimize the support of these unwanted modes. Numerical simulations of various cavity dimensions and beam parameters allow us to optimize both the cavity eigenmode formation process and the electron-wave interaction to achieve oscillation with a single cavity eigenmode. CST Microwave Studio (CST MWS) and ATK's Magic 3D were used for the electromagnetic field analysis within the PSL structure and electron-wave interactions respectively. Previous Strathclyde research into PSLs and sources has been published in references [5-8].

II. NUMERICAL RESULTS

To realize a device that offers narrow bandwidth, single frequency output with high power, numerical analysis allows us to optimize the interaction region. This analysis has shown that an optimized system involves an incident near cut-off azimuthally symmetric $TM_{0,3}$ VF and an induced $HE_{7,1}$ SF. The annular electron beam [9] operates with a beam thickness of less than 1.0 mm and an inner radius of 2 mm as it passes within 0.5 mm of the lowest radial point of the PSL structure. These parameters result in a peak output power of ~300 kW at a primary operating frequency of 103.6 GHz with an interaction efficiency of ~10 %. Higher frequency harmonics are seen in figure 1 (b) although they share only ~1% of the total output power. This does however imply the potential of a device that produces 3 kW at ~200 GHz using a 20 A beam and accelerating voltage U = 150 kV. Figures 1(a), (b) and (c) demonstrate this interaction:

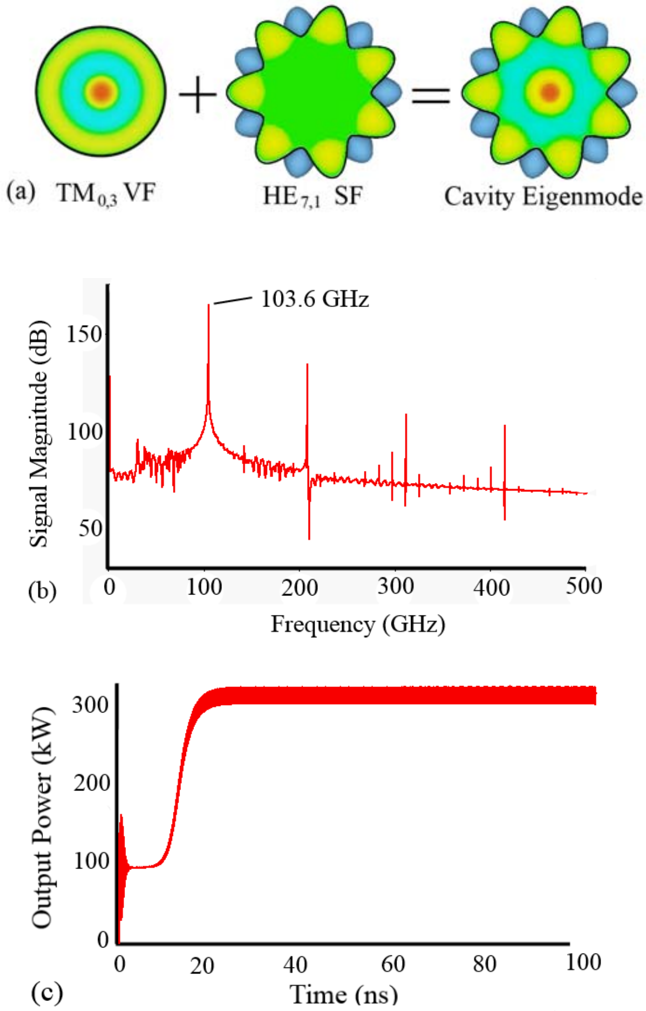

Figure 1: (a) CST MWS visualization of the volume field (VF), surface field (SF) and cavity eigenmode. (b) Output frequency spectrum as seen in Magic 3D. (c) Graphical display of the output EM power in Magic 3D.

III. Experimental Setup

Operating at W-band frequencies (75 – 110) GHz determines the physical parameters of the system. For internal reflection and hence cavity formation to occur at the correct frequency, the longitudinal period of the PSL structure must be chosen so as to 'select' out the appropriate wavelengths from the electromagnetic field as it grows within the structure. This means that the rest of the system must be designed around this wavelength. For W-band output, a system with a longitudinal period, d_z = 1.6 mm, such as this system also requires a cavity radius that optimizes the beam–wave interaction at this frequency. In order to reduce the electrical breakdown effect that high power, high frequency systems are prone to, an oversized structure with respect to the radius is used where the radius is chosen to minimize the possibility of breakdown while restricting the number of modes that can be produced. Numerical simulation of the system using Magic 3D has enabled the development of a set of physical parameters that provide stable and optimal output. An applied accelerating voltage of 150 kV with a flat top B-field section of 1.8 T that encloses the system from the cathode to the opposing end of the 2D PSL produces an output power of approximately 300 kW at a frequency of 103.6 GHz with an efficiency of 10 %.

The actual physical manufacturing of the system incorporates a number of processes and materials. The entire system is drawn using Autodesk Inventor 2014 and each subsequent component is then produced utilizing either high resolution 3D printing technology or a more traditional milling process. The PSL interaction region and anode structures are created using the 3D printing process and results in a silver (92.5%) – chromium (7.5%) alloy material that has excellent conductivity but is stronger than pure silver. The interaction region is held under a constant but relatively low vacuum of approximately $1\text{x}10^{-6}$ Pa which is contained by a setup of nickel plated stainless steel components, some of which are 3D printed and some are milled. Figure 2 demonstrates a cross section of the interaction region as seen in Autodesk Inventor with the red cylinder through the centre being the annular electron beam and the 2D PSL interaction cavity located in the centre of the solenoid.

IV. Summary

Numerical analysis has demonstrated that the electron-wave interaction in a Cherenkov maser can be optimized by tailoring the physical parameters of the PSL interaction cavity region. Single mode output was achieved at 103.6 GHz by implementing 7 azimuthal variations in a structure with an unperturbed inner radius of 4 mm. Any modification of these values would result in a change to the cut-off frequency of the VF mode and hence would adversely affect the cavity eigenmode formation. Investigation of the number of longitudinal periods required for efficient beam-wave coupling to occur determined that 16 periods was the optimum value which produced the output power seen in figure 1(c).

With a peak output power of ~300 kW and with an efficiency of 10 % this device is aimed at conducting a proof of principle experiment demonstrating electron beam interaction with a wave formed when the volume field and surface field are coupled in an oversized 2D PSL cavity. The application of PSLs has the potential to deliver high average power, efficient, compact electromagnetic wave sources in the challenging THz frequency range.

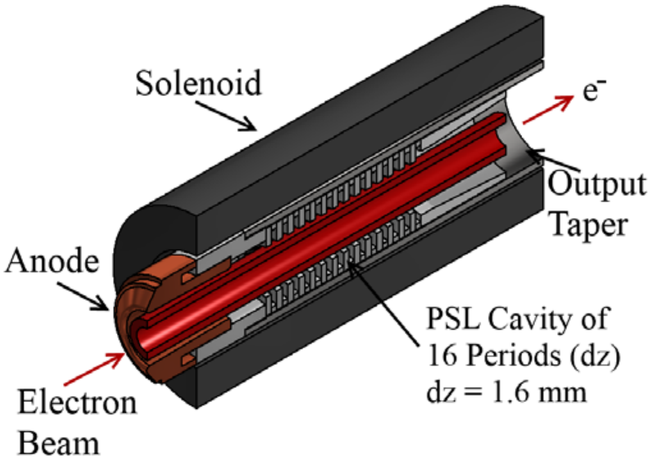

Figure 2: A schematic of the experimental design for the interaction region. The red component is the electron beam, entering from the electron gun end and propagating in vacuum through the PSL section and passing through the output taper where it will be eventually collected on the vacuum vessel inner walls, as the confining magnetic 'guide' field magnitude decreases.

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