Powerful, over-moded 0.14 THz radiation source

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***Abstract*—In this paper we present the design of a complex two-dimensional cylindrical surface structure for use within a 0.14 THz radiation source. This frequency range is relevant for several applications, including communications. The precise dimensions and parameters must be carefully chosen to optimize radiation output at 0.14 THz.**

I. INTRODUCTION

High power, high frequency radiation can be generated by passing a thin, annular electron beam through a cylindrical interaction region with a two-dimensional (2D) corrugated inner surface. To achieve high power at shorter wavelengths, the diameter of the 2D periodic surface lattice (2D PSL) interaction cavity is scaled up in size and therefore overmoded. The surface current induced around the periodic azimuthal and axial surface perturbations is scattered into a surface field which decays exponentially towards the center of the cavity. A coupled, eigenmode can form if this surface field is coupled with a suitable $TM_{0,N}$ volume field [1-8]. This volume and surface field coupling allows for mode selection in the oversized PSL. To produce high power at a chosen frequency, the transverse dimensions and parameters of the 2D PSL and electron beam must be carefully selected. Once optimum parameter values and dimensions have been found using analytical and numerical methods, the cylindrical PSL cavities can be manufactured using copper electrodeposition or additive manufacturing techniques [3,9].

We present the theoretical and numerical design of a cylindrical 2D PSL for use within a 0.14 THz radiation source for applications that include communications, imaging, radars, plasma diagnostics and environmental sensing.

To compare numerical calculations made using the particle in cell (PIC) code solver of CST Microwave Studio (CST MWS) with analytical theory, a cylindrical 2D PSL, with diameter D = 4.4 mm ($D/\lambda \sim 2$) is studied. The corrugation inscribed on the inner wall of the cylindrical 2D PSL structure is described by,

$$r = r_0 + \Delta r cos(k_z z) cos(\bar{m}\varphi)$$

where r_0 is the mean radius, Δr is the amplitude of the azimuthal and axial corrugation, and $\bar{m}$ is the number of azimuthal variations around the cylindrical cross section. The azimuthal period $d_m = 2\pi r_0/\bar{m}$ is constrained by the wave-beam coupling criterion $\bar{m} \le 2\pi r_0/\lambda\gamma$ where γ is the relativistic factor and λ is the wavelength. The axial period $d_z = 2\pi/k_z$ of the structure is shortened to facilitate coupling with the electron beam and is calculated by matching the electron beam velocity

$$v_z = c\left(1 - (1/\gamma)^2\right)^{1/2}$$

to the velocity within the PSL slow wave structure. Effective wave-beam coupling is observed when the axial period is

$$d_z = \left(\lambda^2 - (\lambda/\gamma)^2\right)^{1/2}$$

and $\lambda \sim d_m$. We consider an electron beam with a 50 A current and an accelerating potential of $V = 50$ kV immersed in an applied magnetic field of 0.5 T. The PSL shown in Fig.1 has a corrugation amplitude of 0.1 mm, $\bar{m} = 5$, $d_m = 2.76$ mm $d_z = 1.14$ mm and length $L = 8d_z$ in addition to two tapered period lengths at the input and output ends of the structure. The CST MWS simulation was run for 50 modes over an electron beam duration of 50 ns. The electron beam must be suitably thin and sufficiently close to the corrugated wall in order to intercept the exponentially decaying surface field. A beam thickness of 0.2 mm was chosen and the beam was positioned with a separation of 0.2 mm from the metal lattice wall.

II. RESULTS

Strong coupling between the electron beam and cavity modes was observed for the cylindrical PSL with $\bar{m} = 5$ and $d_z = 1.14$ mm shown in Fig.1. Contour plots of the dominant $TM_{3,1}$ eigenmode are presented in Fig. 2. A very small longitudinal magnetic field component of 0.2 Am^{-1} exists due to the azimuthal corrugation. The eigenmode cut-off frequency of 138.27 GHz is ~0.2 GHz lower than that of a pure $TM_{3,1}$ mode. The CST MWS simulations show that the total power output of the orthogonal and degenerate $TM_{3,1}$ modes typically exceeds 0.49 MW at a frequency of 0.14 THz. Fig.3 shows resonances at 0.11 THz, 0.12 THz, 0.14 THz, 0.15 THz, and 0.17 THz despite the 1.07 mm axial distance from the cathode reflector to the 2D PSL being $\lambda/2$ for a frequency of 0.14 THz. An analytical dispersion plot [2, 4-7] of the eigenfield inside the PSL which is formed by the $TM_{0,2}$ volume mode coupled with the ± 1 surface field spatial harmonics is given in Fig.4. An interaction between the electron beam and the PSL cavity eigenfield can be observed when the electron beam dispersion is described by,

$$\omega = k_z v_z + \frac{2\pi}{d_z} v_z$$

The electron beam intersects the lower branch of the coupled cavity eigenfield dispersion at three different frequencies. The numerical resonances at approximately 0.12 THz, 0.14 THz and 0.17 THz correlate with the theoretical predictions shown in Fig.4 for which it was assumed that the surface field is coupling with the $TM_{0,2}$ volume mode. The resonance at 0.11 THz has a wavelength similar to that of the azimuthal period $d_m = 2.76$ mm and corresponds to the $TM_{2,1}$ mode.

The efficiency of the device may be improved by further optimization of the parameters to increase the power output at 0.14 THz and suppress the resonances at other frequencies.

Parameters such as the corrugation amplitude affect the strength of the coupling of volume and surface fields and can therefore change the appearance of the cavity eigenfield dispersion diagram and the frequencies at which the electron beam and eigenfield interact. The transverse dimension of the cylindrical PSL can be further increased to $D/\lambda \geq 4$ where the structure is highly overmoded. The technique of volume and surface mode coupling on the surface of the 2D corrugation can be used to maintain sufficient efficiency as the number of modes within the structure is increased. Eventually, higher values of $D/\lambda \geq 10$ may become viable. A method of forming a high-Q supermode inside an oversized cavity using the Talbot effect has been proposed by Oparina et al. [10].

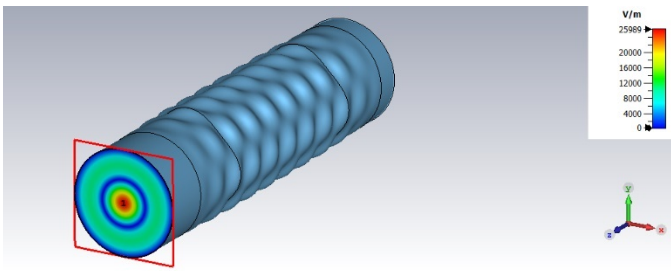

Fig. 1. Illustration of the CST Microwave studio cylindrical 2D PSL model, showing the $TM_{0,2}$ volume mode propagating through the structure. The PSL has length $L = 8d_z$ and 2 taper periods at both the input and output ends of the structure.

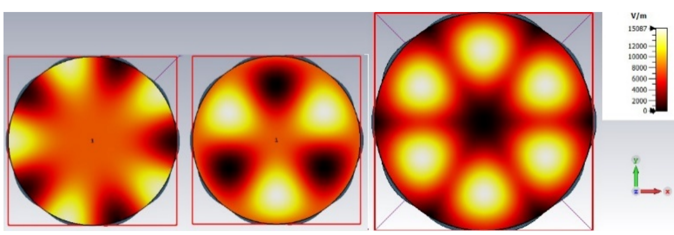

Fig. 2. Contour plots of the longitudinal magnetic H_z field component of 0.23 Am^{-1}(left) and the longitudinal electric E_z field component (center). The absolute electric field is shown on the left. The $TM_{3,1}$ mode is the dominant eigenmode at 138.3 GHz.

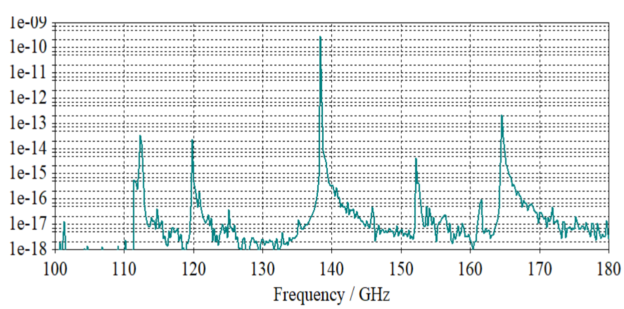

Fig. 3. Output power spectrum of the overmoded radiation source using a 50kV, 50A electron beam and a cylindrical 2D PSL, with $r_0 = 2.2$ mm, $\bar{m} = 5$, and $d_z = 1.14$ mm, simulated using CST MWS.

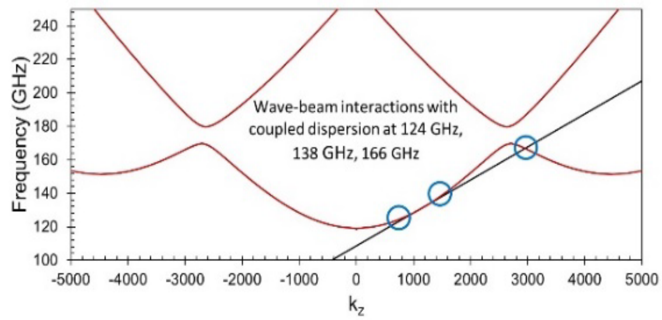

Fig. 4. Analytical dispersion plot showing the coupled eigenmode formed by the $TM_{0,2}$ volume mode and the ± 1 spatial harmonics of the surface mode. The electron beam line shows possible wave-beam interactions between the 2D PSL with $r_0 = 2.2$ mm, $\bar{m} = 5$, $d_z = 1.14$ mm and the 50 kV electron beam.

III. Summary

The production of 0.14 THz radiation generated by passing a compatible electron beam through an overmoded cylindrical PSL interaction cavity has been demonstrated. Good agreement between analytical dispersion diagrams and the numerical modelling carried out using CST Microwave Studio has been observed. This work can be extended to study cylindrical PSL cavities with an increased transverse size, and is also relevant to different frequencies depending on the chosen dimensions and parameter values.

IV. Acknowledgments

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