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Powerful radiation source at 0.35 THz based on overmoded, periodic cavities

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***Abstract*— We present the design of a cylindrical, two-dimensional periodic surface lattice structure intended for use as the interaction region of an electron beam driven, pulsed Cherenkov source. We demonstrate production of high peak power radiation output at 0.35 THz. The interaction region is oversized and mode selection is achieved by the coupling of volume and surface fields to form a coupled cavity eigenmode. The work is also applicable to different frequencies, and the diameter of the cavity can be increased to achieve higher output powers.**

Keywords—periodic structure, mm-wave, THz, electron beam, radiation source, mode coupling, Cherenkov

I. Introduction

Advances in communications, imaging, radars, plasma diagnostics, spectroscopy and environmental sensing rely on the availability of sources that can deliver adequate power at mm-wave and THz frequencies. Powerful radiation sources at about 350 GHz are sought after due to the lower atmospheric attenuation at this frequency. One method of generating high power radiation at shorter wavelengths involves guiding a thin, annular electron beam close to the corrugated inner wall of a cylindrical two-dimensional periodic surface lattice (2D PSL)[1-8].

A cylindrical 2D PSL is made by creating a shallow, periodic corrugation on the inner surface of a cylindrical waveguide, either using additive manufacturing [3,9] or by depositing copper on a carefully designed aluminum former, which is subsequently dissolved. The 2D PSL structures presented in this paper can accommodate both volume and surface fields. The volume field exists within the cylindrical waveguide region while the localized surface field is bound to the inner wall and decays exponentially towards the center of the structure. The surface field exists due to the surface current induced around the azimuthal and axial 2D corrugation.

In conventional sources, the interaction cavity dimensions are scaled according to the intended operating frequency, with the diameter being comparable to the wavelength λ. In the 2D PSL structures presented in this work, the diameter D is scaled up in size so that the ratio D/λ is approximately 2.7. Compared to other radiation sources, where the output power is restricted by the diameter, especially at shorter wavelengths, a source incorporating a 2D PSL, in contrast to a 1D PSL [10], is capable of producing higher output power at mm-wave and THz frequencies. This increase in diameter often leads to multi-mode excitation. This problem can be resolved if the volume and surface fields within the 2D PSL are coupled to form a cavity eigenfield, enabling mode selection in the oversized cavity.

Precise dimensions and parameters of the 2D PSL must be selected in order to achieve high output powers at a given frequency. In this paper, we present the theoretical and numerical design of a cylindrical 2D PSL for use within a 0.35 THz radiation source.

Another promising technique involving the formation of a high-Q supermode inside an oversized cavity using the Talbot effect has been proposed by Oparina et al. [11].

II. Design and parameters of 2D PSL

The corrugation on the inner surface of the cylindrical 2D PSL structure is defined by the equation

$$r = r_0 + \Delta r cos(k_z z) cos(\bar{m}\varphi) \quad (1)$$

where r_0 is the mean radius, Δr is the amplitude of the corrugation, and $\bar{m}$ is the number of azimuthal variations. For coupling between the electron beam and the PSL eigenfield, $\bar{m} \leq 2\pi r_0/\lambda\gamma$ where γ is the relativistic Lorentz factor. The azimuthal period is $d_m = 2\pi r_0/\bar{m}$ and the axial period $d_z = 2\pi/k_z$ is shortened to facilitate coupling with the electron beam. The PSL was designed with a length of $L = 8d_z$in addition to a taper of length d_z at both the input and output ends of the structure. The full set of parameters of the PSL structure is given in table 1.

III. Analytical Dispersion analyis

Analytical dispersion diagrams are plotted by solving the coupled dispersion equation derived in [2,5]. Fig.1 shows the coupled eigenmode of the 2D PSL, formed by the near cut-off $TM_{0,3}$ volume mode and the ± 1 surface field spatial harmonics. For strong wave-beam coupling, the dispersion of the electron beam depends on the axial period of the 2D PSL and is given by the relation

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

Backward wave interactions between the electron beam and the fundamental and the +1 spatial harmonics of the coupled eigenmode are observed at approximately 348 GHz when the

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accelerating potential of the electron beam is 50 kV.

PSL Parameters		
mean radius (mm)	r_0	1.18
axial period (mm)	d_z	0.35
number of azimuthal variations	$\bar{m}$	7
corrugation amplitude (mm)	Δr	0.06

Table 1. 2D PSL parameters

IV. CST Microwave Studio Results

The 2D PSL was modeled using the particle in cell (PIC) solver of CST Microwave Studio (CST MWS). Fig. 2 illustrates the PSL and cathode geometry. A transparent PEC grid is located between the cathode and the start of the taper of the 2D PSL to improve the quality of the beam and guide the beam close to the inner corrugated wall. Annealed copper was chosen as the lossy metal background to simulate the copper 2D PSL. The electron beam is immersed in a strong, applied magnetic field of 5.0 T that guides the thin annular beam close to the wall. The 50 keV electron beam has a relatively low current of 2.5 A .Calculations were made for 50 modes, over a 30 ns duration.

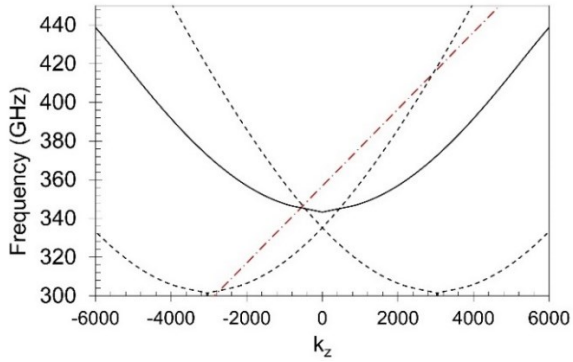

Fig. 1. Analytical dispersion diagram showing the fundamental (solid black line) and ±1 spatial harmonics(dashed black lines) of the 2D PSL coupled eigenmode. The 50 keV electron beam line (dot-dash red line) intersects the fundamental and +1 spatial harmonic at around 348 GHz showing the potential for a backward wave interaction close to 0.35 THz.

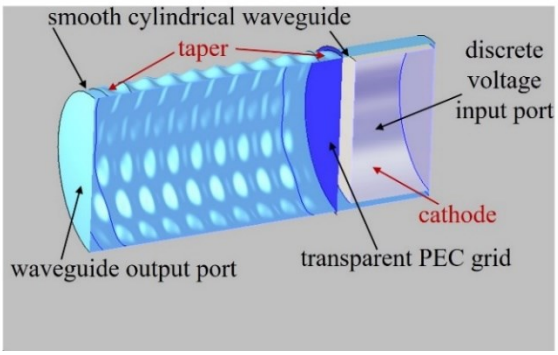

Fig. 2. Diagram showing geometry and set-up of cathode and 2D PSL and the grid located between the cathode and the taper of the 2D PSL.

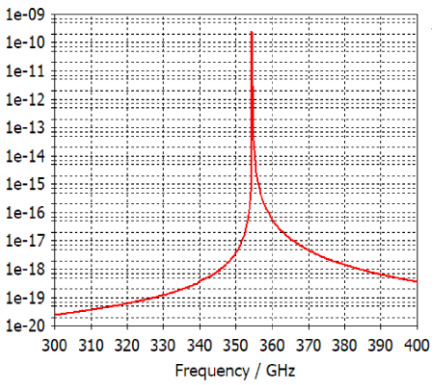

Fig. 3. Output power spectrum of the overmoded radiation source based on the lossy copper 2D PSL with r_0=1.18 mm, $\bar{m}$=7 and d_z= 0.35 mm modeled using CST MWS.

Fig. 3 shows the radiation output observed at 354 GHz, within reasonable agreement of the 348 GHz theoretical prediction. The output spectrum is dominated by the pair of orthogonal, degenerate $TM_{5,1}$ modes, located close in frequency to the nearly cut-off, azimuthally symmetric $TM_{0,3}$ mode.

V. Summary

We have demonstrated the potential for cylindrical 2D PSL structures to be used as interaction cavities within electron beam driven sources. The results show 34 kW of output power at ~0.35 THz can be achieved by driving a suitable annular electron beam through an oversized, cylindrical 2D PSL. The CST MWS simulations show that the efficiency of the device typically can exceed 27 %. Good agreement between the theoretical dispersion diagrams and CST MWS simulations has been reported. This work can be extended to consider PSLs with an increased transverse size and higher D/λ values, and is also applicable to different frequencies depending on the specific dimensions and PSL parameters.

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