Numerical Analysis and Experimental Design of a Cherenkov Maser based on a 2D Periodic Surface Lattice

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ABP

Atoms, Beams & Plasmas

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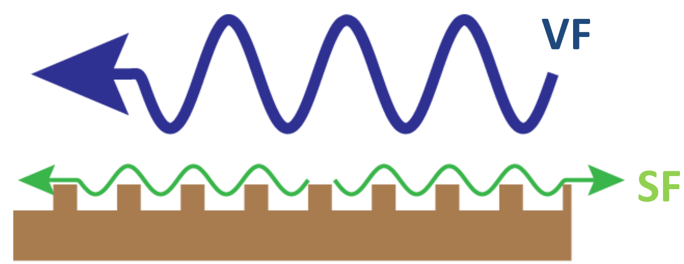
Theory

The Two-Dimensional Periodic Surface Lattice (2D PSL) provides a mechanism for inducing coupling of an incident near cut-off ($TM_{0,n}$) Volume Field (VF) and the $HE_{m,1}$ Surface Field (SF) that is formed around the perturbations when the Bragg conditions are satisfied.



$$\bar{k}_{\pm} = \bar{k}_i - \bar{k}_s \qquad \bar{m} = \pm(m_1 - m_2)$$

The perturbations are defined analytically as:

$$\mathrm{r} = \mathrm{r}_0 + \Delta \mathrm{r} \cos\left(\bar{\mathrm{k}}_z \mathrm{z}\right) \cos(m_{azi} \bar{\phi})$$

Where r_0 is the unperturbed waveguide radius, Δr is the perturbation amplitude and $\bar{k}_z$ and m_{azi} are the longitudinal wavevector and the azimuthal variation.

Coupled mode theory describes the VF/SF interaction:

$$\frac{dA_V}{dz} + i\kappa A_S = 0 \qquad \frac{dA_S}{dz} - i\kappa A_V = 0$$

A_V , A_S = Amplitudes of the volume and scattered waves. The amplitude of the incident volume wave is dependent on the amplitude of the scattered wave through a coupling coefficient κ.

I. V. Konoplev, A. R. Phipps, et al, Appl. Phys. Lett. 102, 141106 (2013)

Dispersion of Coupled Fields inside Cylindrical Periodic Surface Lattice

$$\left(\omega_e^2-\Lambda^2\right)\left[\Lambda^4-2\Lambda^2\left(2+\Gamma^2+\omega_e^2\right)+\left(2-\Gamma^2+\omega_e^2\right)^2\right]=2\alpha^4\left(2-\Gamma^2+\omega_e^2-\Lambda^2\right)$$

- α is the normalised coupling coefficient
- Λ is the normalised wave vector
- ω_e is a variable angular frequency
- The detuning parameter Γ is a function of the geometry of the structure

.

$$\Gamma = \frac{\lambda_c}{d_z}$$

where λ_c is the cut-off wavelength of the volume field inside the cylindrical waveguide and d_z is the longitudinal lattice period.

I.V. Konoplev, A.J. MacLachlan, C.W. Robertson, et al., "Cylindrical, periodic surface lattice - Theory, dispersion analysis, and experiment", *Appl. Phys. Lett.*, **101**, 121111, 2012.

Dispersion Analysis of Cylindrical Periodic Surface Lattice: Γ=2.3

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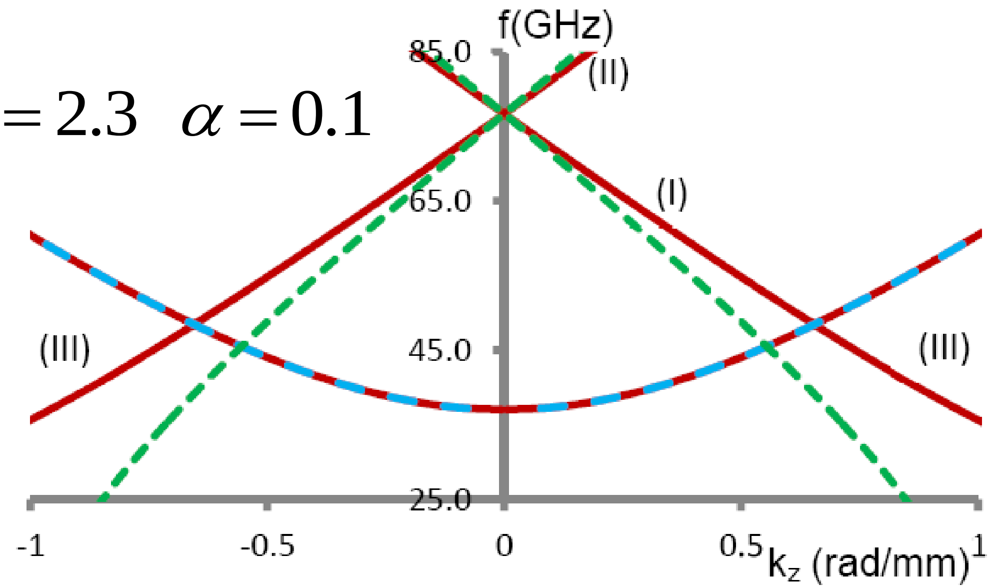
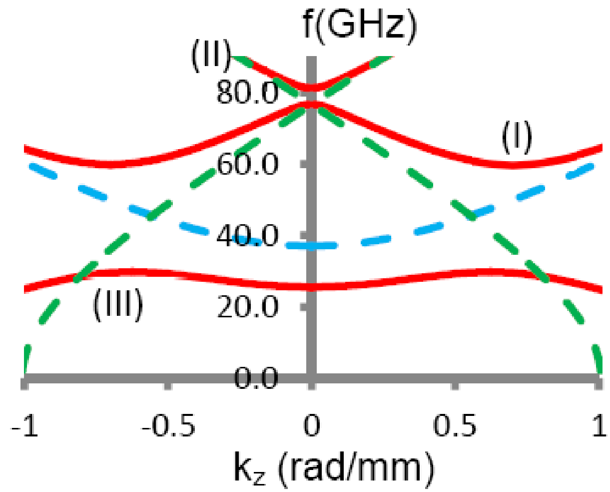
$\Gamma = 2.3 \quad \alpha = 0.1$





$\Gamma = 2.3 \quad \alpha = 1$

Uncoupled surface field =

Uncoupled volume field =

Coupled dispersion =

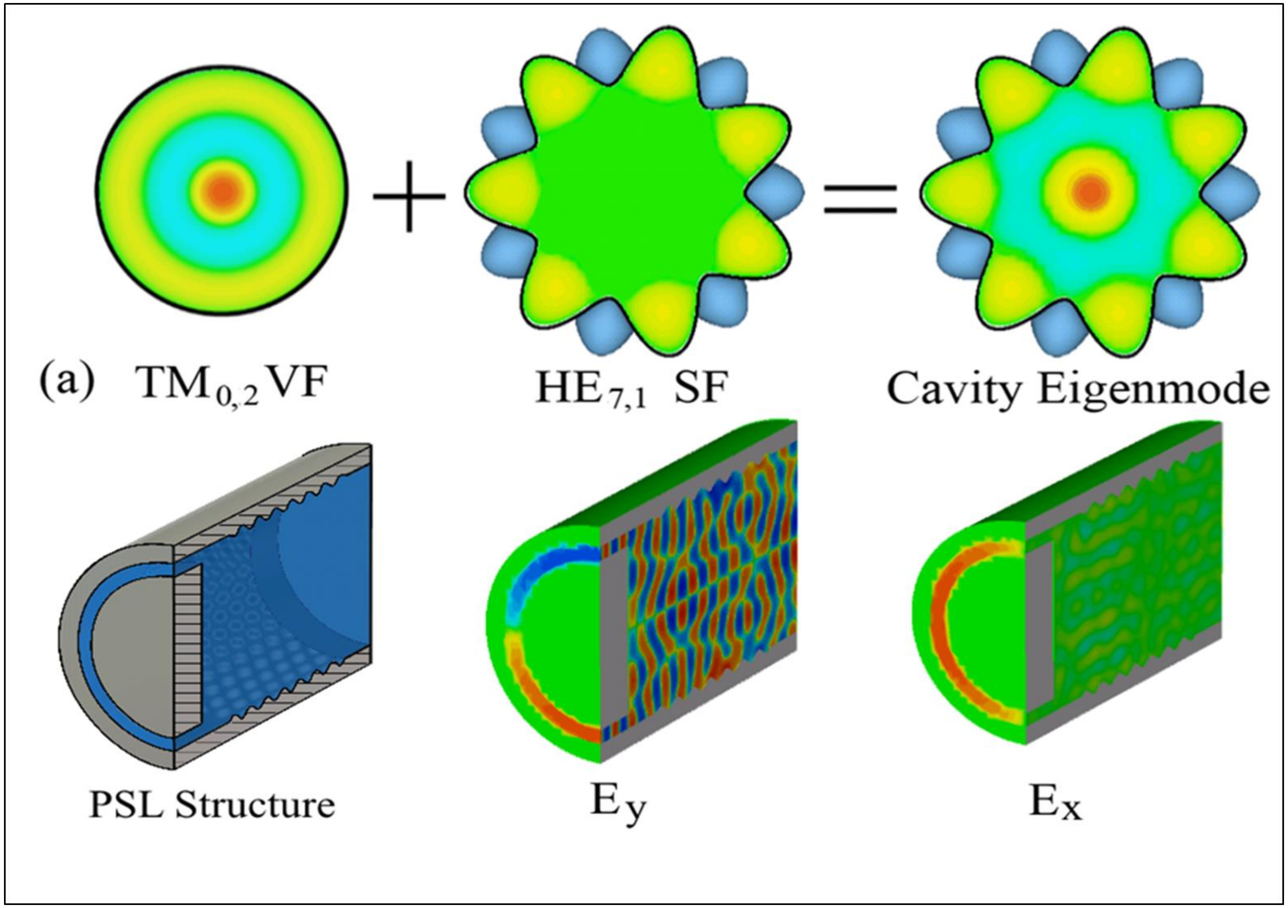
- The position of maxima and minima points $\partial f / \partial k_z = 0$ of the dispersion indicate the positions of the cavity eigenmodes.
- The $\partial f / \partial k_z$ sign variation illustrates that slow forward or backward waves may be observed.

I.V. Konoplev, A.J. MacLachlan, C.W. Robertson, et al., “Cylindrical, periodic surface lattice as a metadielectric: Concept of a surface-field Cherenkov source of coherent radiation”, *Phys. Rev. A.*, **84**, 013826, 2011.

CST Microwave Studio Simulations

PSL Parameters (Cherenkov Maser structure):

- Frequency = ~100.9 GHz:
- Azimuthal variations = 7
- Inner radius = 4 mm
- Perturbation amplitude = 0.85 mm
- Prominent modes = $TM_{0,1}$,$TM_{0,2}$ and $TM_{0,3}$



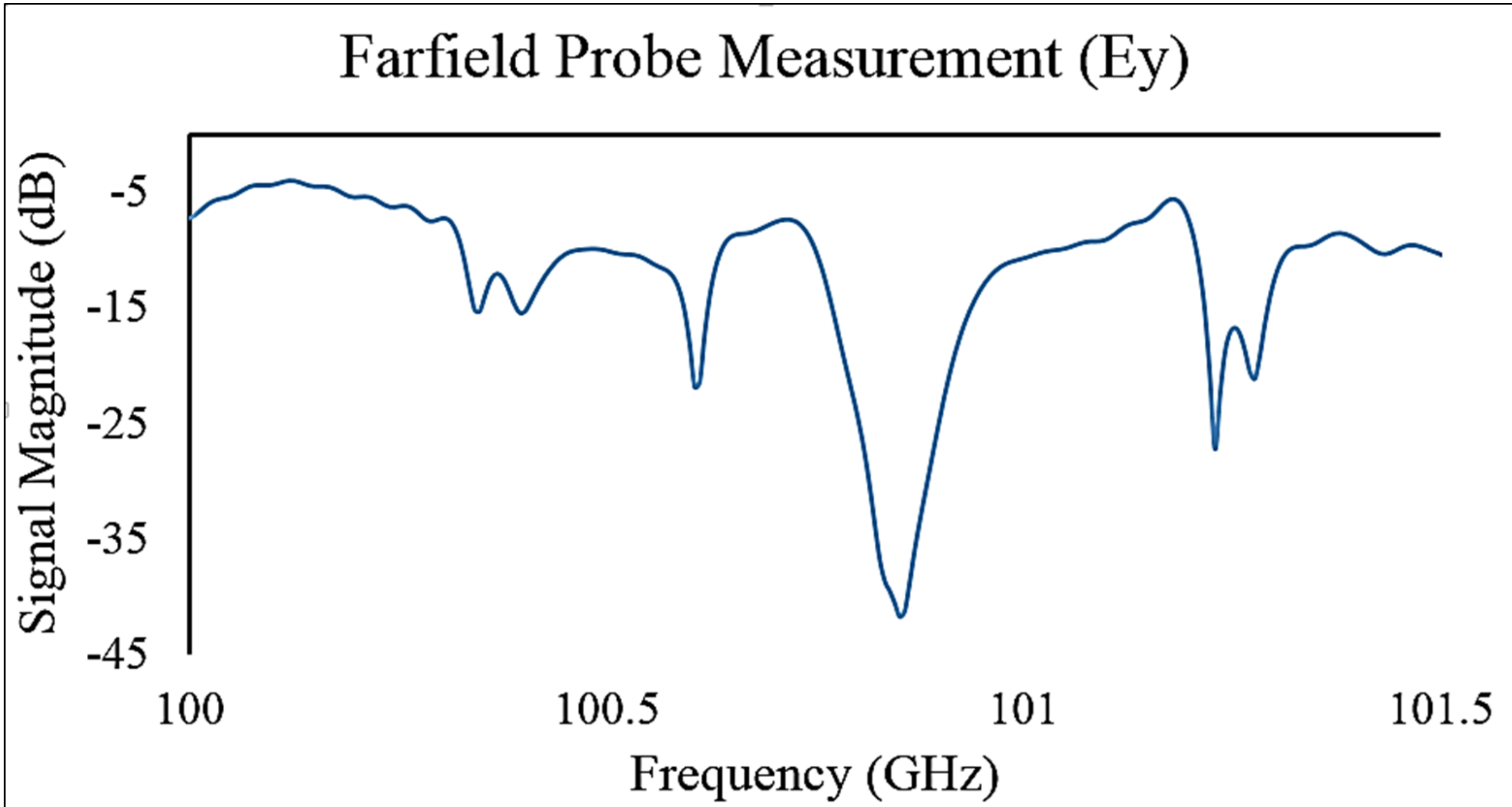
Construction of W-band 2D PSL

2D PSL

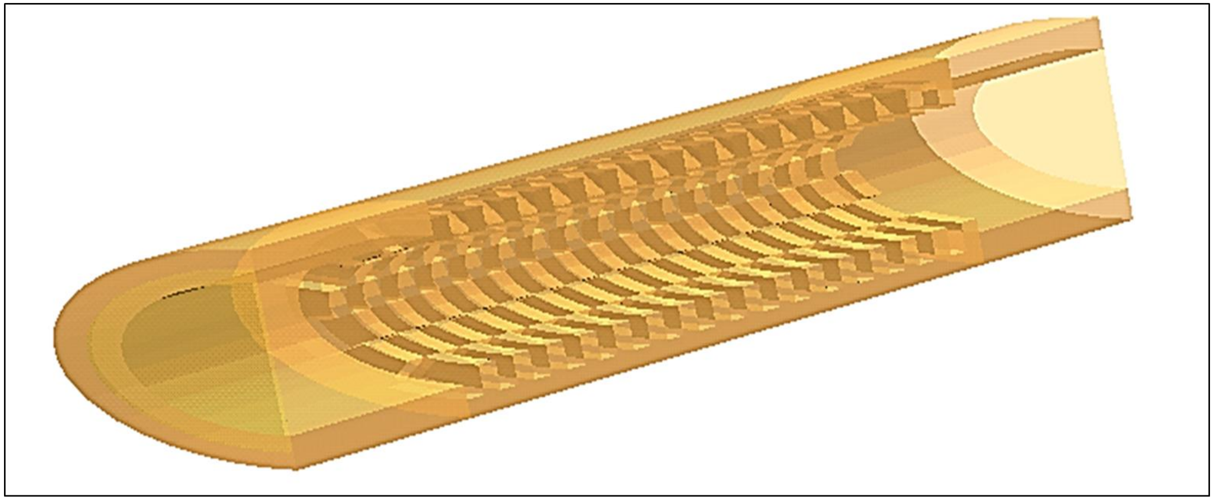
- 3D printed wax former (high resolution)
- Molten silver (92.5%) – chromium (7.5%) alloy deposited into mold
- +/- 125 micron resolution

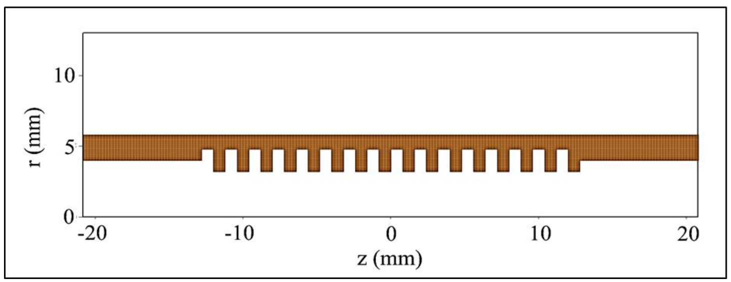
Parameters	
Unperturbed Radius	4 mm
Azimuthal Variations	7
Longitudinal Period	1.6 mm
Number of Periods	16
Perturbation Amplitude	0.85mm

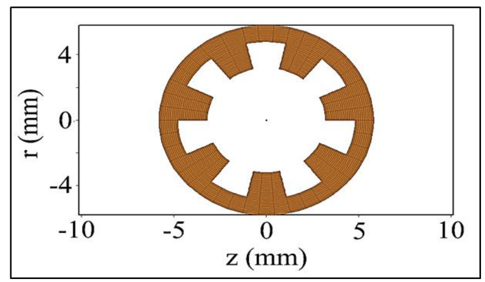
Vector Network Analyser measurements of W-band 2D PSL



MAGIC 3D Simulations

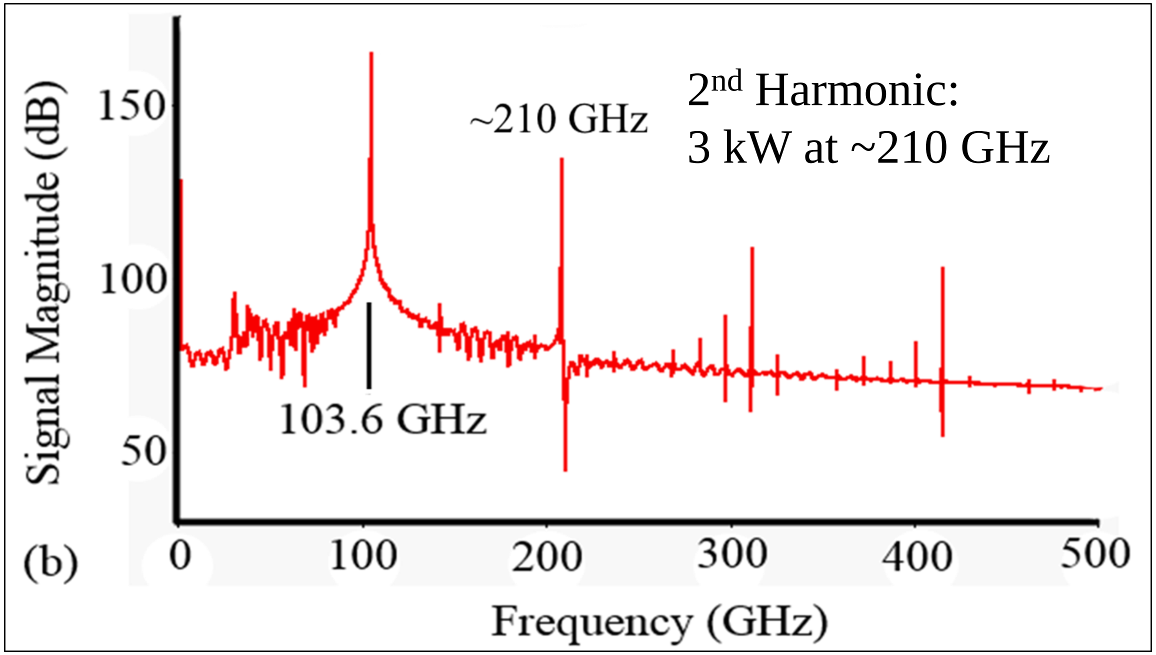


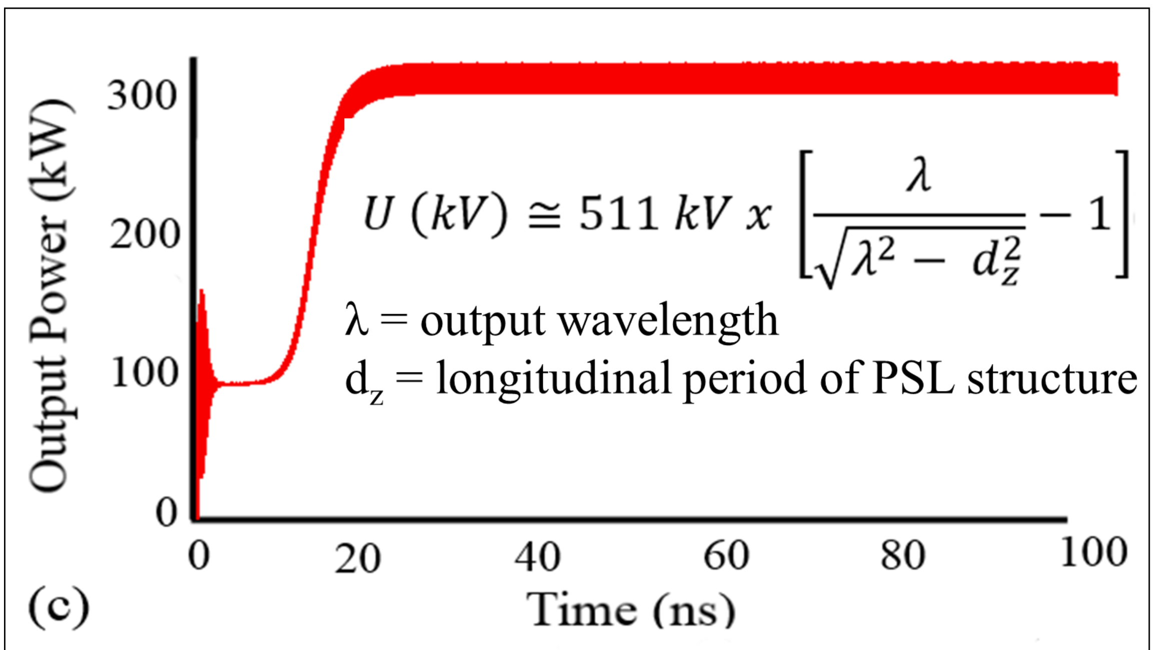




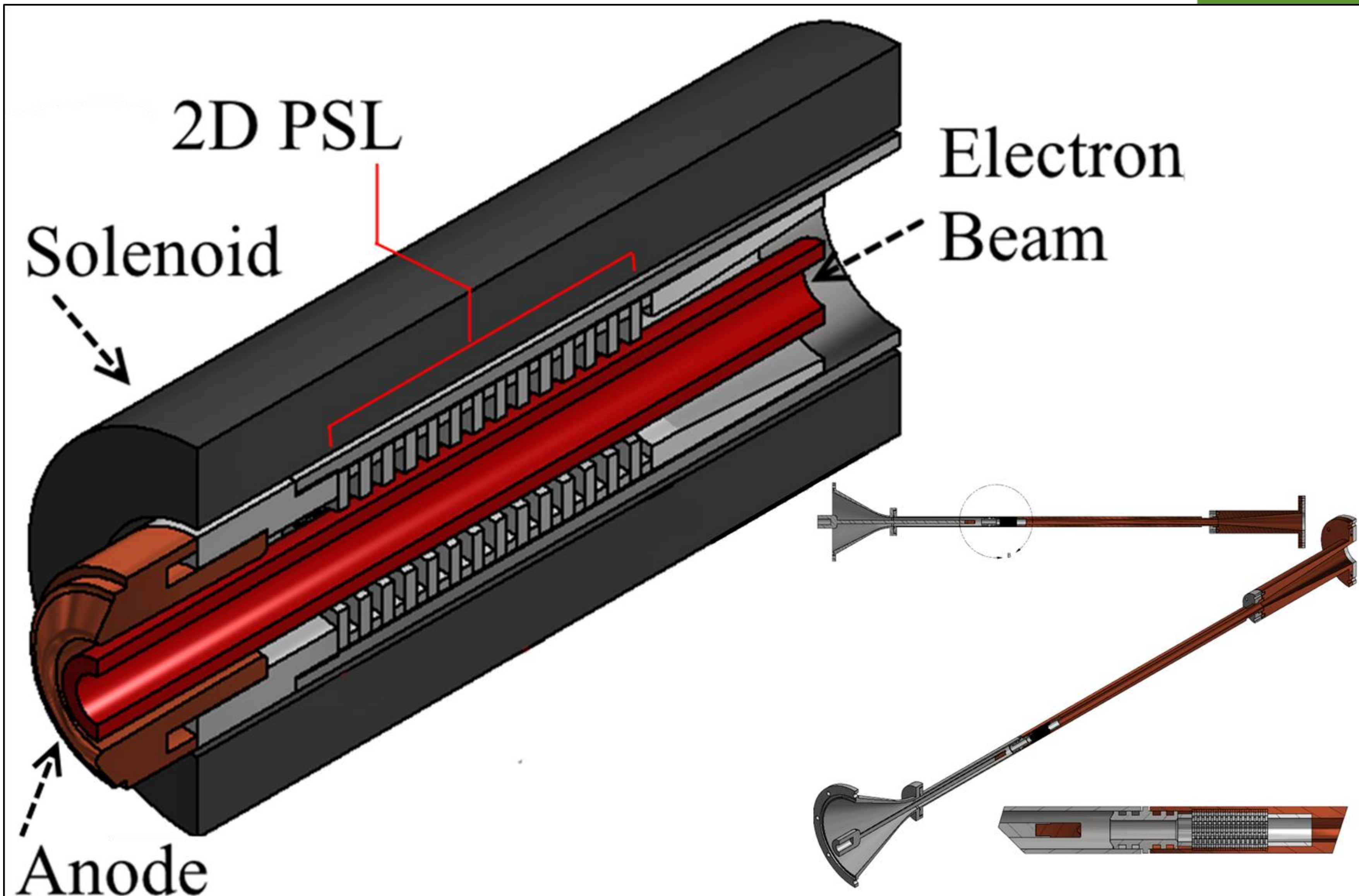
- Square perturbation to optimize simulation time
- 16 Longitudinal periods
- ~300 kW Output power
- Frequency 103.6 GHz
- ~10 % Efficiency
- Accelerating voltage = 150 kV
- 1.8 T B_z
- 20 A Hollow electron beam

MAGIC 3D Simulations



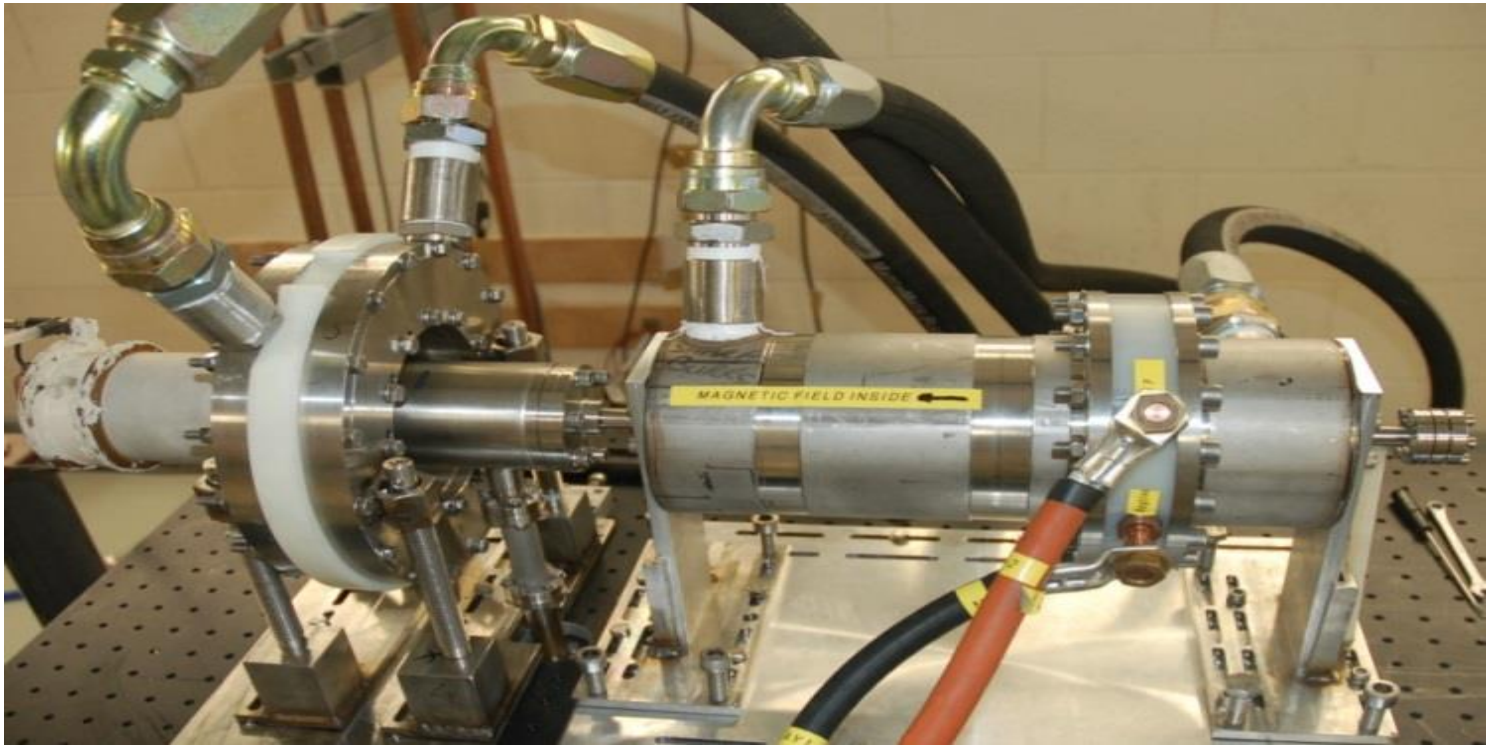


Experimental – Design



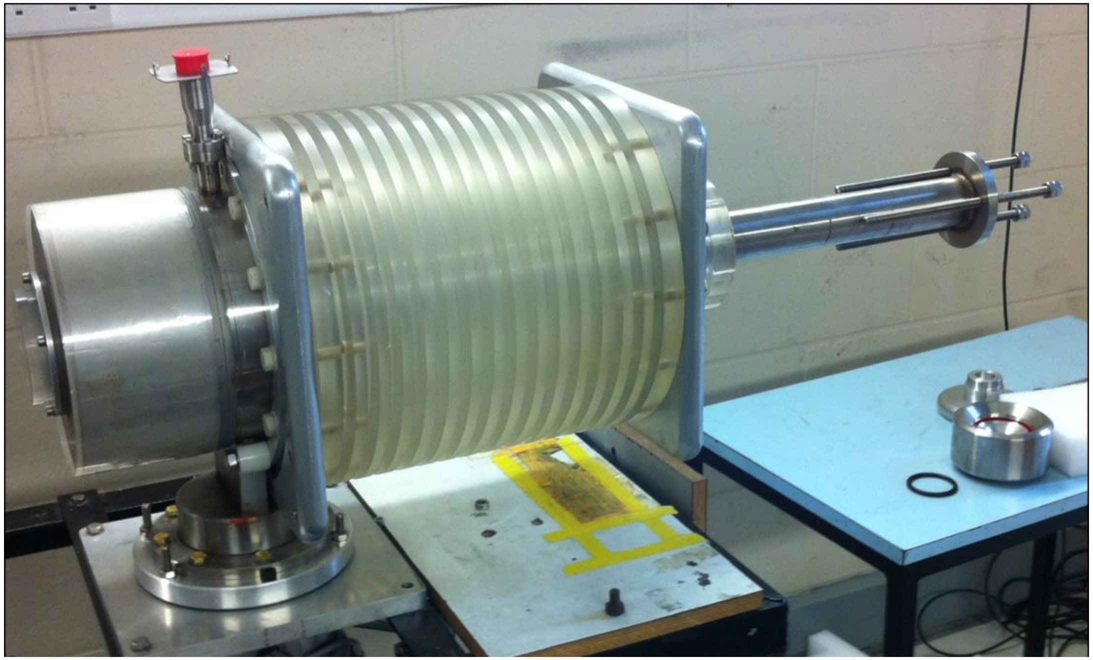
Experimental – Cavity, Vacuum envelope and output horn

Experimental Apparatus (cont)



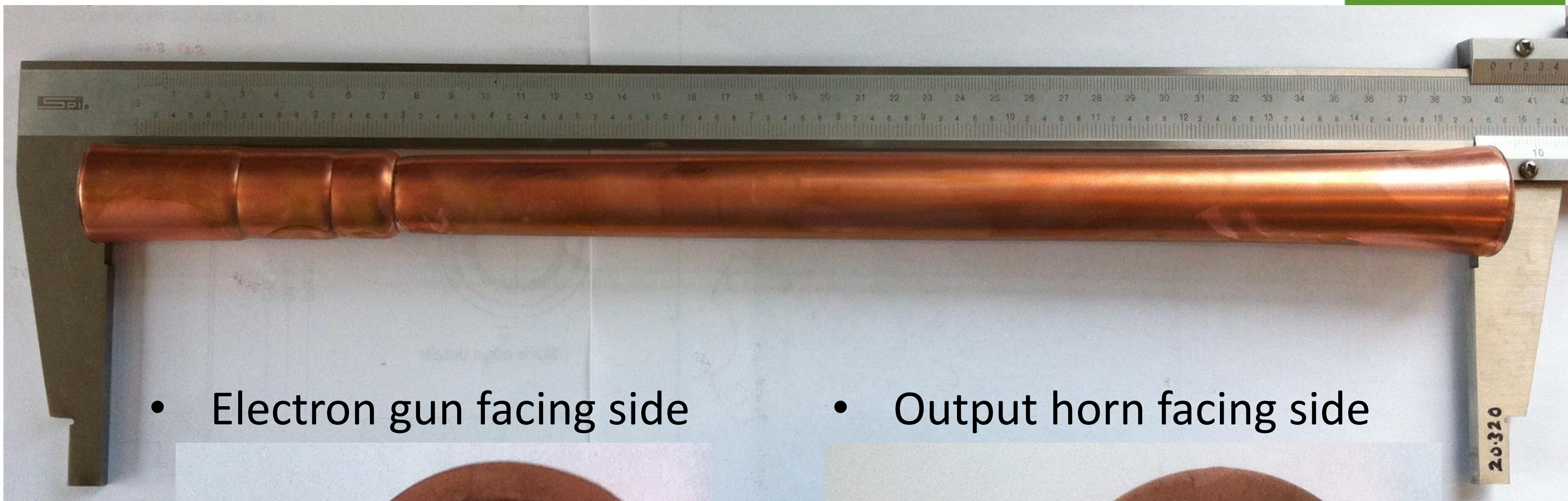
- DC conventional coil, designed, constructed and tested
  - B-field up to 2 T

Diode of electron gun and HV power supply constructed

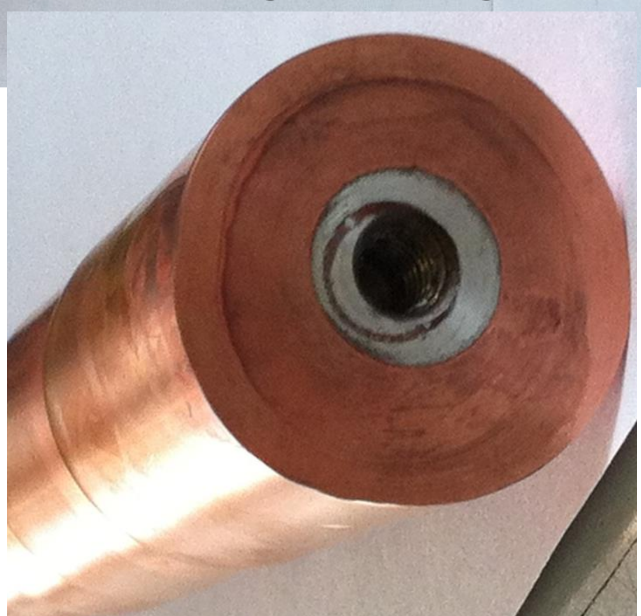


- HV power supply, cable Blumlein generator
- Cold field emission cathode
  - Beam current 20 A
  - Beam voltage 150 kV
  - Pulse duration 100 ns

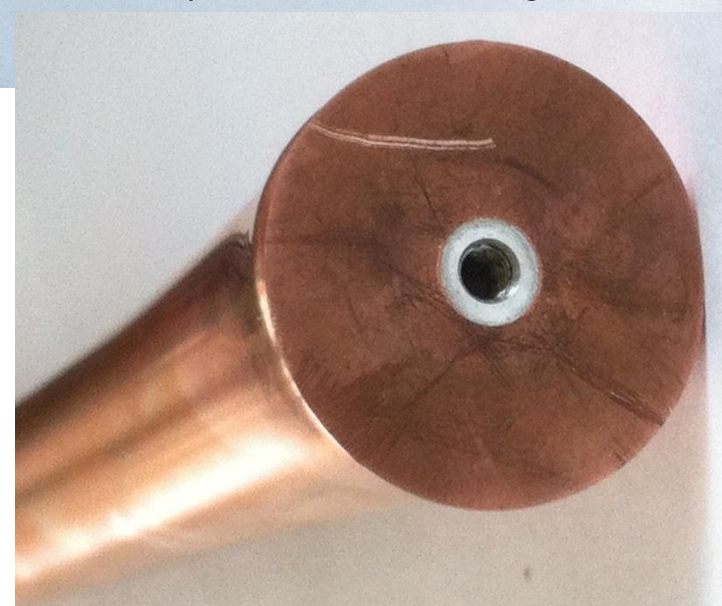
Vacuum envelope under construction



- Electron gun facing side



- Output horn facing side



Conclusion

- Successful cavity formation within W-band 2D PSL structure observed
- Good agreement between experimental results and numerical analysis
- Operating frequency and bandwidth dependent on perturbation amplitude
- Operational parameters can be ‘hard coded’ into structure
  - 2D PSL constructed from silver using a 3D printing technique
- Determined range of design parameters for experimental W-band Cherenkov maser
- Beam/wave interaction demonstrated using MAGIC 3D
  - 100GHz, 300kW, 10% efficient Cherenkov maser oscillator
- Construction of W-band Cherenkov Maser incorporating a 2D Periodic Surface Lattice near completion
  - Electron gun
  - Solenoid
  - Vacuum envelope
  - High voltage power supply

Work Schedule

- ❑ Install W-Band 2D PSL in experimental apparatus
- ❑ Measure electron beam properties
  - ❑ Beam current, voltage and position
- ❑ Carry out W-Band 2D PSL Cherenkov maser experiments
  - ❑ Measure frequency, power and mode structure
- ❑ Compare measured results with theoretical predictions

		J	A	S	O	N	D	J	F	M
WP1.1	System Under Vacuum	■	■							
WP1.2	Beam Measurements			■	■					
WP1.3	mm-Wave Measurements					■	■			
WP1.4	Thesis Write-up	■	■	■	■	■	■	■	■	■

Acknowledgments

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