# Periodic Structures Manufactured by 3D Printing for Electron Beam Excitation of Coherent Sub-Terahertz Radiation

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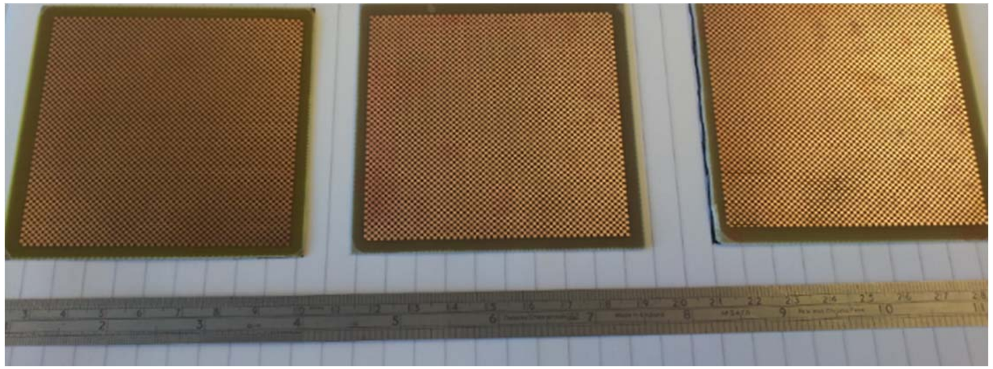
Atoms, Beams & Plasmas

# Objective: MM-wave → THz sources

- To find a route to higher power millimetre waves that can scale to THz frequencies.
- One of the strategies we are using is to increase the transverse dimensions of the interaction region so that the diameter to wavelength ratio is large while avoiding multi-mode operation.
- This approach is particularly attractive for the shorter wavelengths in the mm-wave and THz ranges.
- To avoid multi-mode operation we are using a two dimensional periodic surface lattice (PSL) that sustains a surface mode that couples to a volume mode resulting in eigenmode formation that can be efficiently driven by an electron beam.

# Mode Selection for High-Power, mm-Wave Sources using Periodic Surface Lattice (PSL)

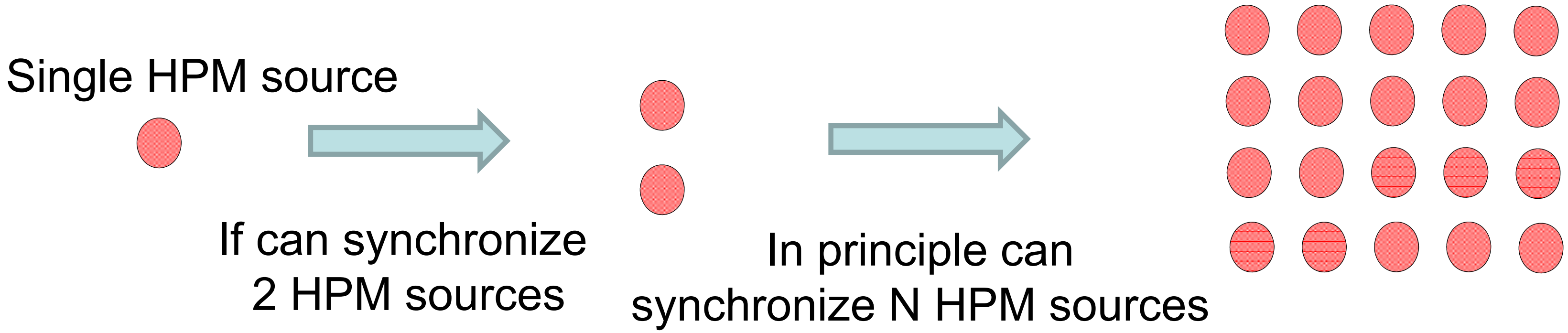


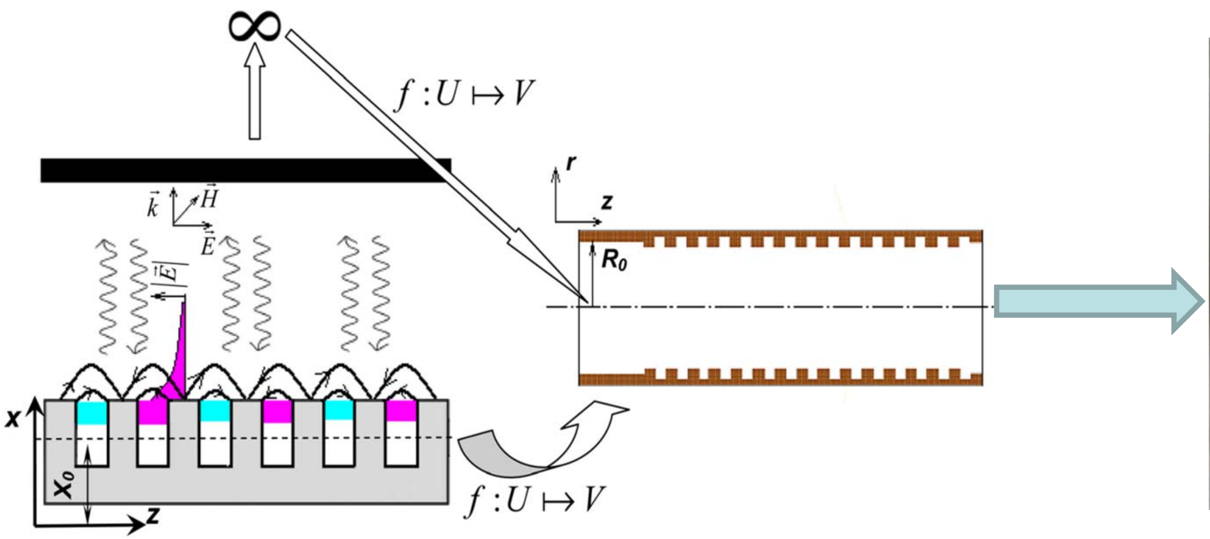
- EM sources are typically designed with cavity dimensions comparable to the operating wavelength - restricts the power of high frequency sources

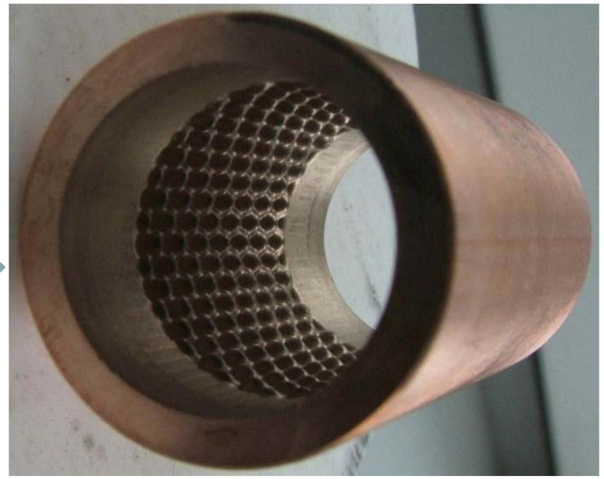
- A Periodic Surface Lattice (PSL) can facilitate coupling of volume and surface fields – allows mode selection in an oversized cavity -high output power output capabilities at mm-wave / THz frequencies

- Planar PSLs studied to demonstrate ‘proof of principle’ coupling – not intended to be deployed within electron beam driven source

# Synchronizing an array of sources

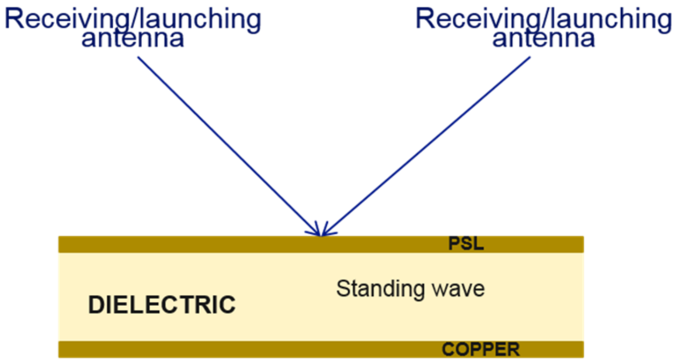


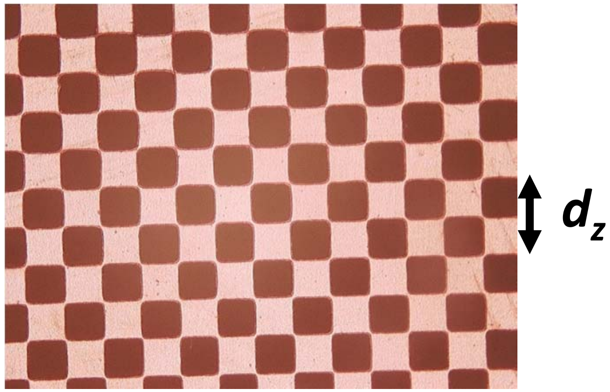



Planar PSLs can be converted into cylindrical structures for use as the interaction region of a mm-wave source via conformal mapping

# Fabrication of Planar PSL Structures




Photograph of planar PSL chemically etched onto copper-backed FR-4 PCB board

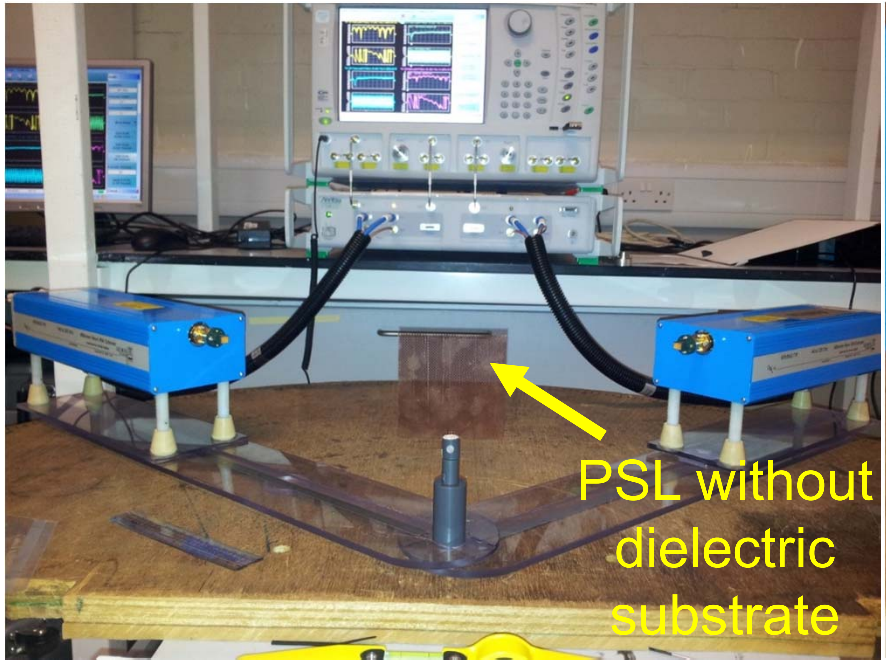
$\varepsilon_r \approx 4.71$ for FR-4 substrate at 140-220 GHz

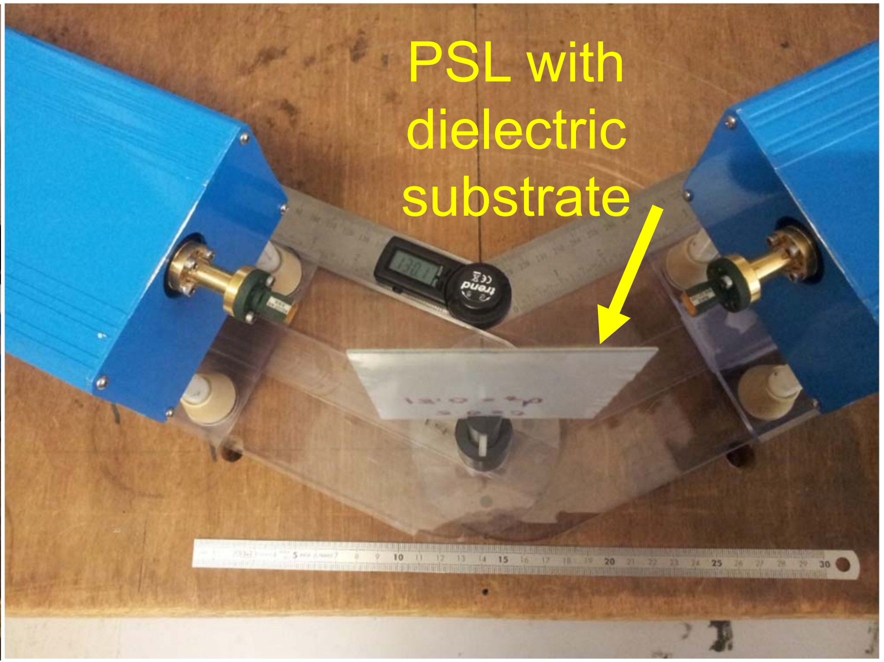
- Planar PSLs were obtained by etching copper coated dielectric (FR-4) sheets of different thicknesses
- Volume field confined in dielectric synchronises the individual surface fields
- PSLs scalable for use at different frequency bands- PSLs have been made for 140-220 GHz and 325-500 GHz bands

(1)Lattice (PSL) only
(2)PSL + Dielectric substrate
(3)PSL + Dielectric substrate
+ copper backing

**Lattice periods 1.50mm, 1.62mm, 1.74mm and 1.94mm**

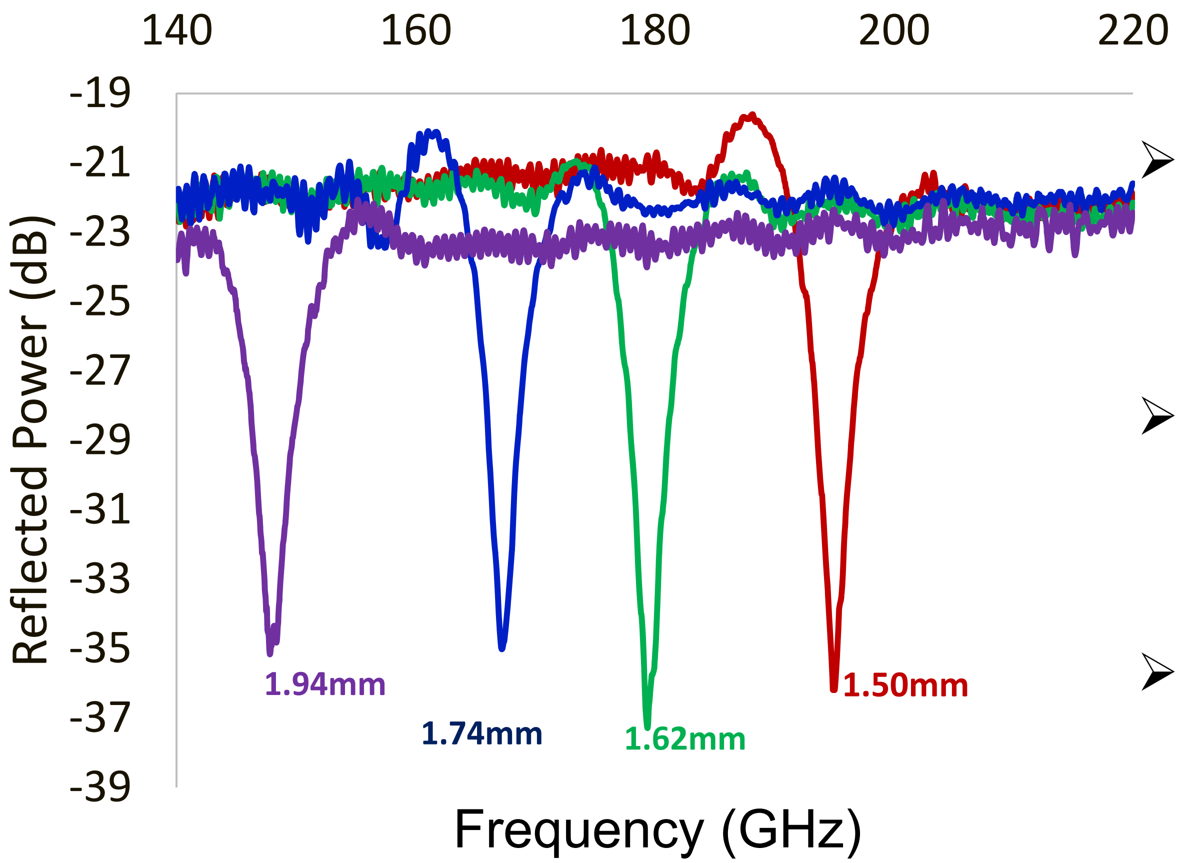
# Experimental Measurements of Planar PSL Structures




- Measurements carried out using Anritsu Vector Network Analyser (VNA) complemented by a pair of high frequency heads
- The angle of the receiving horn was kept equal to the angle of incidence for all measurements

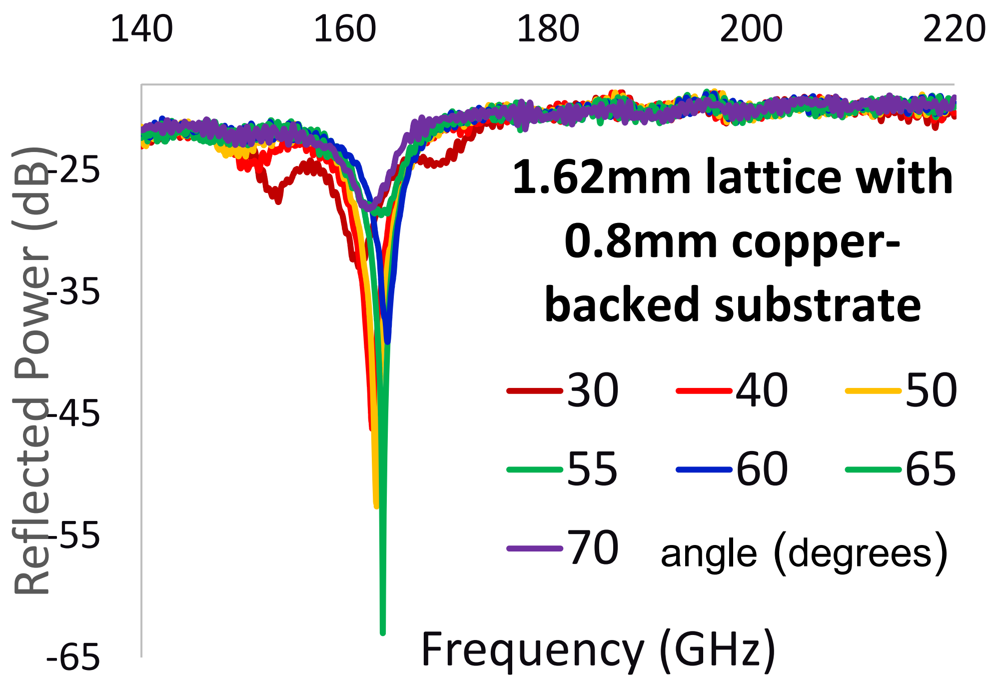
# Measurements of PSLs without Substrates at Fixed Incident Angle (40°)

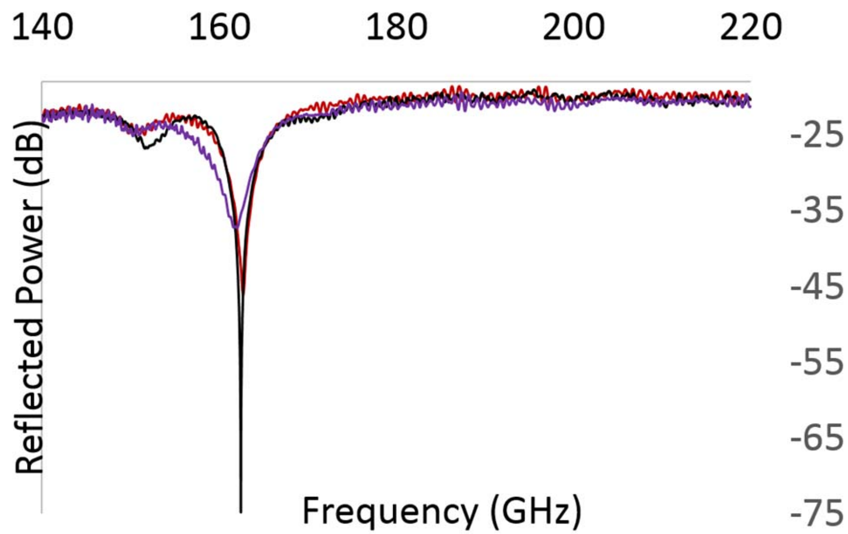



Incident angle= 40°

- PSLs without substrates fabricated and measured to study surface field
- Sharp resonance corresponds to uncoupled surface field
- The frequency of the surface field resonance shifts down with increasing lattice periodicity

# Coherent Eigenmode Formation - PSL with 0.8mm Copper-backed Substrate




*The 3 overlaid traces demonstrate the reproducibility of the measurements.*

- Frequency no longer varies with incident angle – resonance is 'mode-locked' at specific frequency
- Mode-locked resonance indicative of coupled eigenmode formed from coupling of volume and surface fields
- High-Q cavity can be used as interaction region of a novel high power source at high frequencies

# Dispersion Relation for PSLs with Cylindrical & Planar Geometry

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

- Applicable to planar PSLs due to assumption that radius of cylinder is very large ($r_0 \gg \lambda$)
- Valid only when lattice corrugation is shallow ($\Delta r \ll \lambda$)
- Just one specified volume mode (near cut-off $TM_{0,N}$) is considered
- Dispersion equation only considers the fundamental volume field spatial harmonic $n_v = 0$

$$\Gamma = \frac{2\bar{k}_z c}{\left(\sqrt{(\omega_0^v)^2 + (\omega_0^s)^2}\right)}$$

$\alpha$ =normalised coupling coefficient

$\Lambda$=normalised wave vector

$\omega_e$ =variable angular frequency

$\Gamma$= detuning parameter

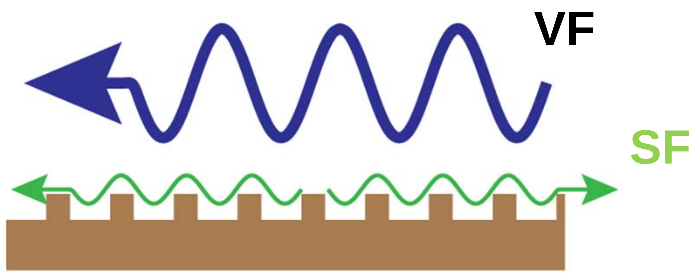
I.V. Konoplev, A. J. MacLachlan, C. W. Robertson et al. ., Appl. Phys. Lett., 101, 121111, 2012

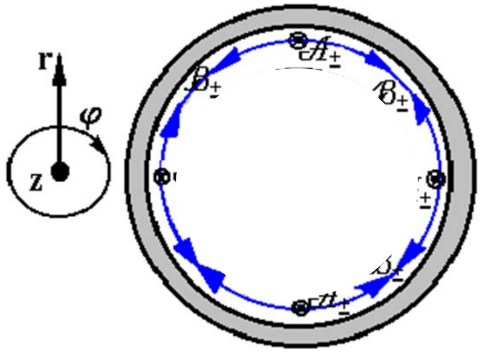
# Planar PSL Conclusions

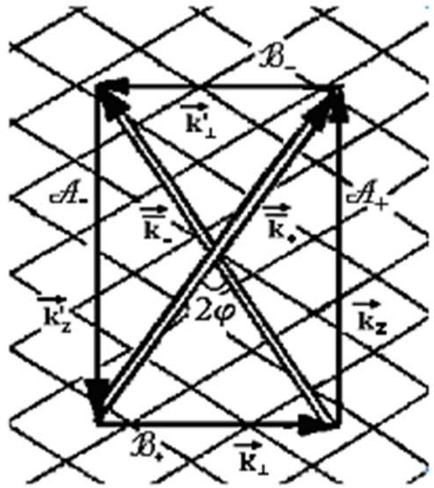
- The PSL’s surface field frequency is determined by the lattice period
- Coherent eigenmode formation due to coupling of volume and surface modes is observed in planar PSL with 0.8mm copper backed substrate
- Mode-locked eigenmode demonstrates PSLs can improve mode selection in oversized cavities
- Copper backing is required to synchronise lattice
- Absorptive losses in thicker dielectric impede lattice synchronisation despite copper backing
- Planar PSL structures are scalable – similar behaviour observed for 0.63mm PSL at 325-500 GHz
- Close agreement between theory developed for oversized cylindrical waveguide and CST MWS modelling of planar PSL when comparing coupled dispersion diagrams with similar parameters
- Good correlation between CST MWS modelling and experimental measurements

# Theory of Cylindrical PSL

The Two-Dimensional Periodic Surface Lattice (2D PSL) provides a mechanism for inducing coupling of an incident ($TM_{0,n}$) 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 Two-Dimensional (2D) Periodic Surface Lattice can be obtained by introducing shallow periodic perturbations at the inner wall of a cylindrical waveguide. The 2D corrugation at the waveguide surface is defined by:

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

where $r_0$ is the mean radius of the unperturbed cylindrical waveguide, $\Delta r$ is the amplitude of the perturbations, $\bar{m}$ is the number of lattice azimuthal variations and $\bar{k}_z = 2\pi/d_z$ is the longitudinal wavenumber of the lattice with longitudinal period, $d_z$.

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

# Electron beam-EM wave interaction

$$\omega = k_z \upsilon_z \mp \frac{\omega_p}{\gamma^{\frac{3}{2}}}$$

$$\omega_b = \left( \frac{|\rho_0| e^2}{\varepsilon_0 m \gamma_0} \right)^{\frac{1}{2}}$$

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

$$\omega = k_z \upsilon_z + \frac{2eB}{\gamma m_0}$$

- $k_z$ is the wave's longitudinal wave number
- 80kV electron beam,
  - $\gamma_T \sim 1.156$
- $v_T$ is the electron beam velocity, 0.5c
- $\alpha = (v_{perp} / v_{para}) = 0.4$
- $v_{para}$ is the e-beam longitudinal velocity, 0.46c
- $v_{perp}$ is the e-beam transverse velocity, 0.19c

- Electrons interact with localized surface field

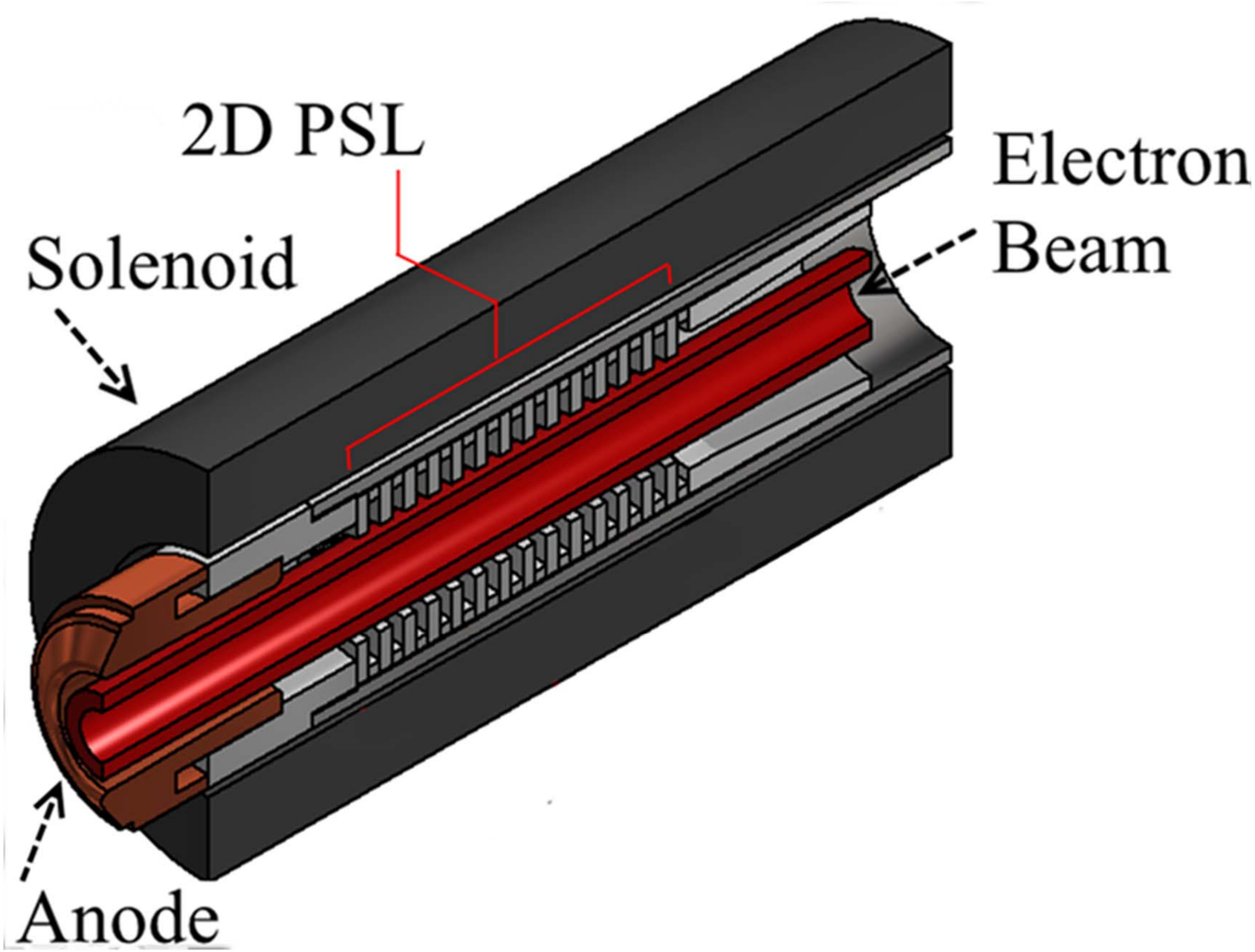
$$f = \frac{c}{d_z} \sqrt{\left(1 - \frac{1}{\gamma^2}\right)} \sim 88\ \text{GHz} \qquad , \quad d_z = 1.6\text{mm}$$

- The accelerating potential for the interaction can be found from the longitudinal period of the lattice and the wave frequency using the equation

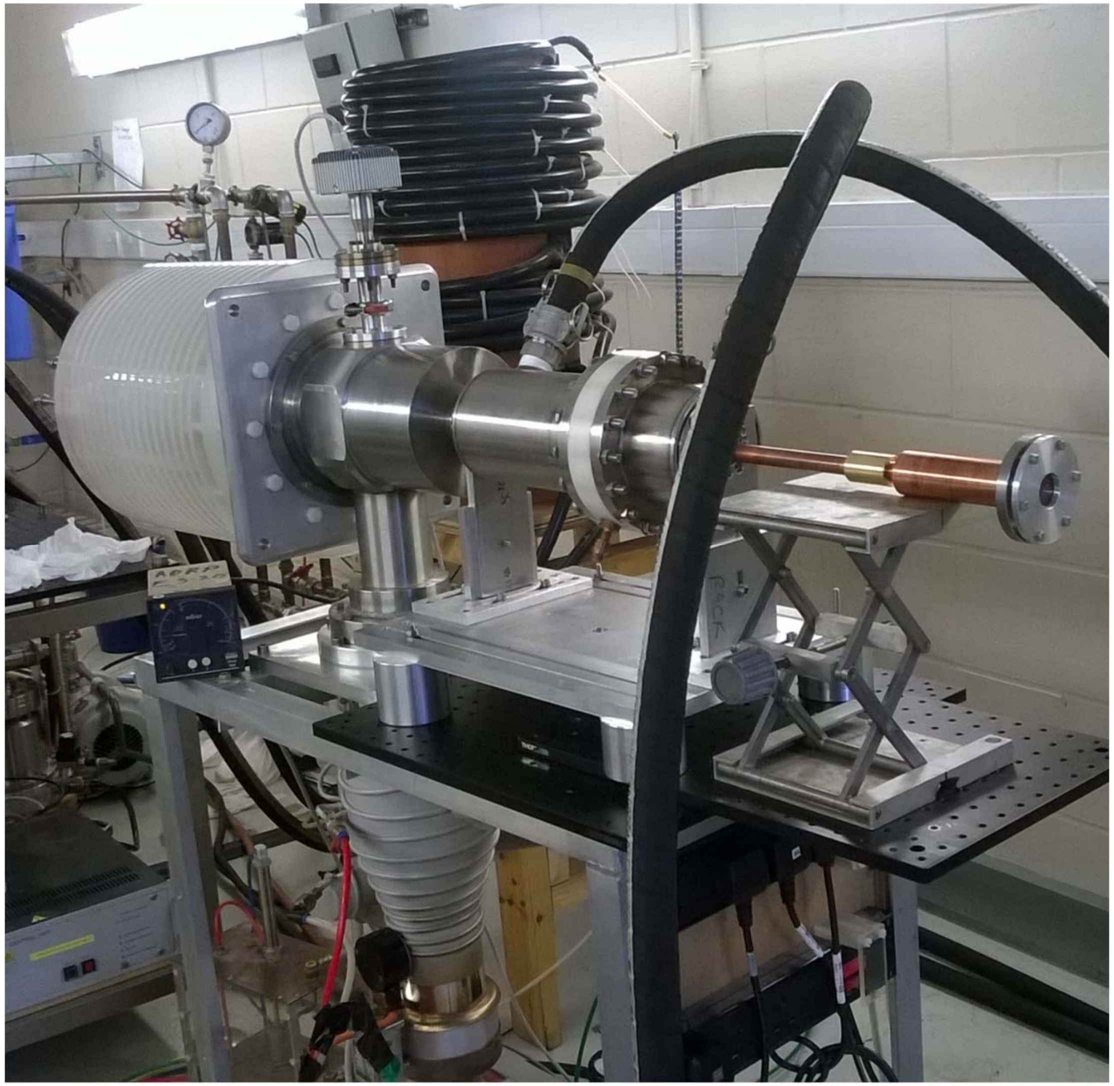
$$U\ (kV) = 511 kV\ x \left[ \frac{\lambda}{\sqrt{\lambda^2 - d_z{}^2}} - 1 \right] \sim 78\ \text{kV}$$

I.V. Konoplev, A.J. MacLachlan, C.W. Robertson, et al., *Phys. Rev. A*., 84, 013826, 2011.

# Experimental Design



# BWO experimental setup



- Diode insulator
  - perspex
- Electron beam source
- BWO interaction region
  - silver 2D PSL
- Copper output horn & Mylar window
- Vacuum jacket, copper & stainless steel
- 16mm bore, 2T solenoid
- Vacuum system, Diffstack backed by rotary pump
  - Pressure 5 x $10^{-6}$ mbar

# Conclusion

- ❑ Constructed W-band BWO incorporating a 2D Periodic Surface Lattice:
  Electron gun, Solenoid, Vacuum envelope, HT power supply
- ❑ Mm-wave excitation within W-band 2D PSL structure observed
- ❑ Agreement between cavity measurements & numerical analysis
- ❑ BWO beam/wave interaction demonstrated using MAGIC 3D
  - − Frequency 81 GHz, Power 50 kW and Efficiency 0.6%

- ❑ Experimental measurements
  - ❑ 80 kV, 100 A, 4 mm diameter annular electron beam
  - ❑ Mm-wave pulses measured
    - ❑ Frequency ~80GHz to 85GHz
    - ❑ Peak power ~30kW+-10kW
    - ❑ Efficiency 0.4%

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# Acknowledgements

We thank the EPSRC UK for the PhD studentships of Alan Phipps and Amy MacLachlan.
We thank the Leverhulme Trust for contributing to this work through an International Network Grant.

**Thank you**

Any questions ?

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