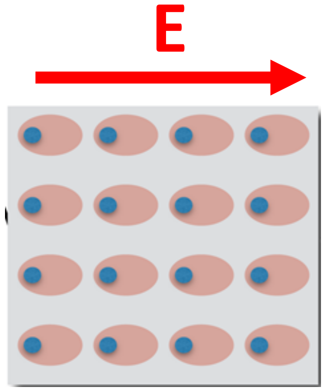
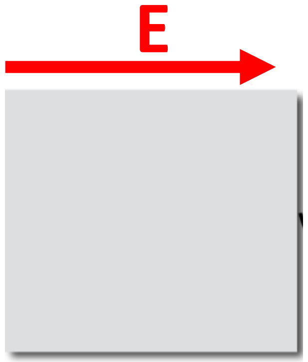
Trip the light fantastic:

Using Artificial Materials to Mediate Novel Wave Particle Interactions.

Prof Rebecca Seviour

History: Effective media theory





$$\vec{D} = \epsilon_0 \vec{E} + \vec{P} = \epsilon \vec{E}$$
$$\vec{B} = \mu_0 \vec{H} + \vec{M} = \mu \vec{H}$$

Constitutive Relations

History: Effective media theory

Homogenization of Materials

- Mossotti, O.F. (1850). Sobre las fuerzas que rigen la constituciòn de los cuerpos. *Memorie di Matematica e di Fisica della Societä Italiana delle Scienze Residente in Modena* 24 (2): 49–74

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System of small (subwavelength) particles

Inhomogeneities in a system << incident wavelength,

→ system appears homogeneous to the wave.

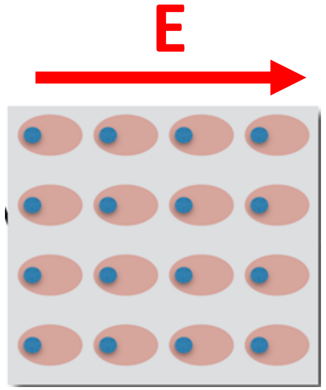
Thomson, W. (1872)

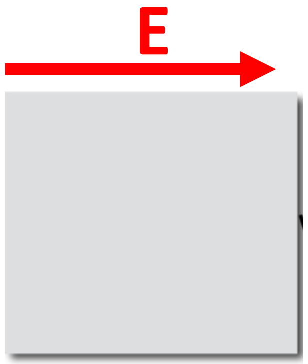
→ Can predict EM behavior of the systems in terms of an effective permittivity and permeability of a macroscopically homogeneous medium.

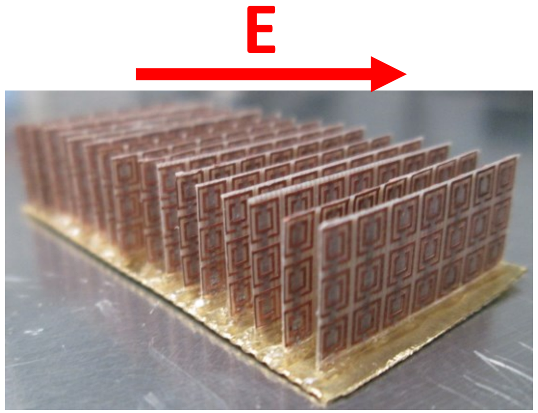
Heaviside, O. (1880)

History: Effective media theory

System of small (subwavelength) particles (homogenized) responds to an EM wave the same as if the system were a collection of molecules with a large polarizability







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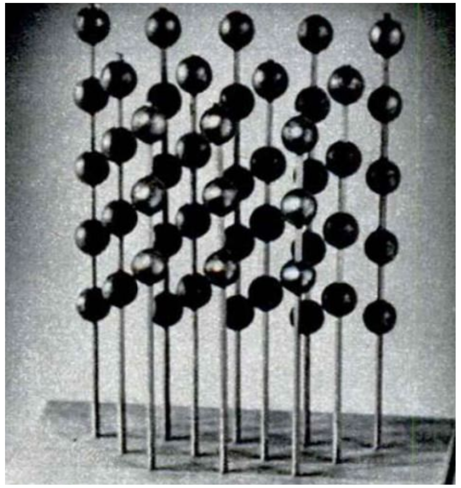

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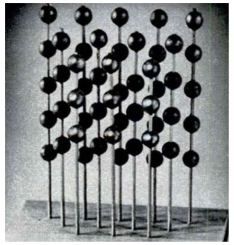

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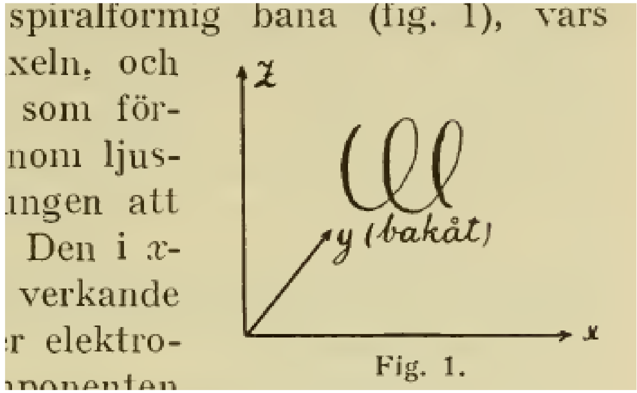


Fig. 1.

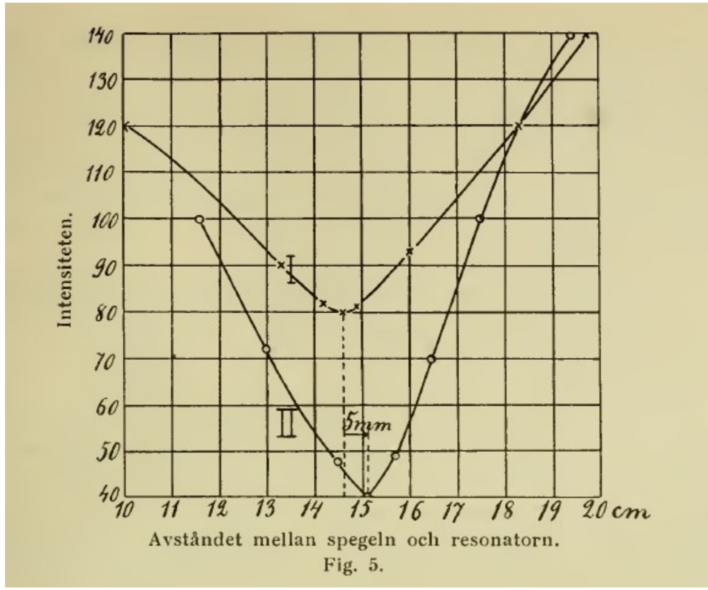
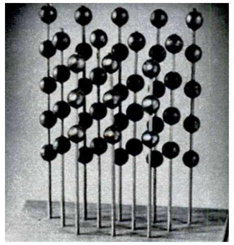


Fig. 5.



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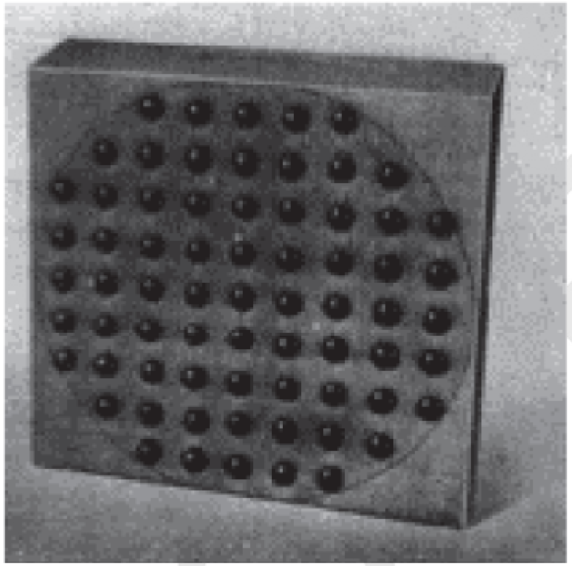

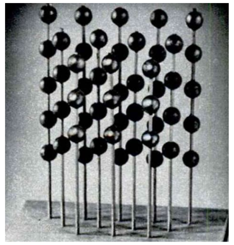

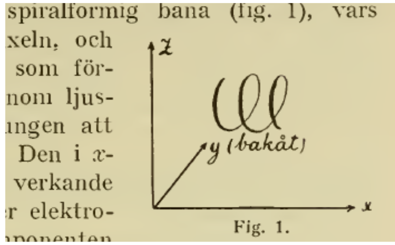

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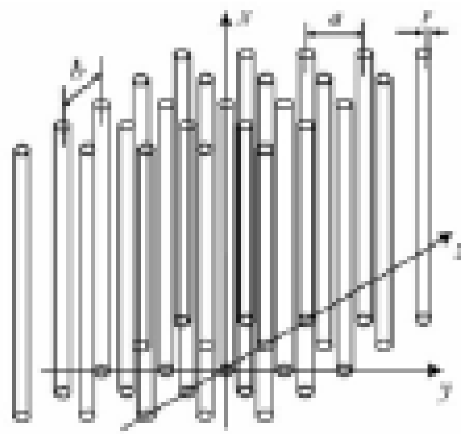

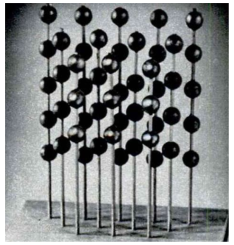

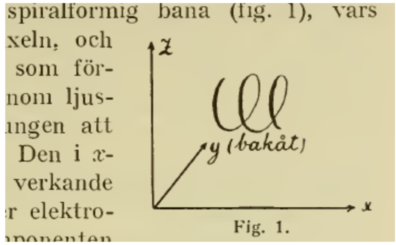
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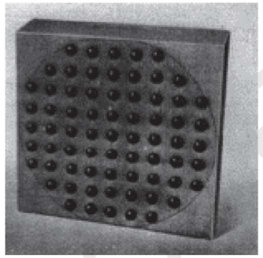
Fig. 1.



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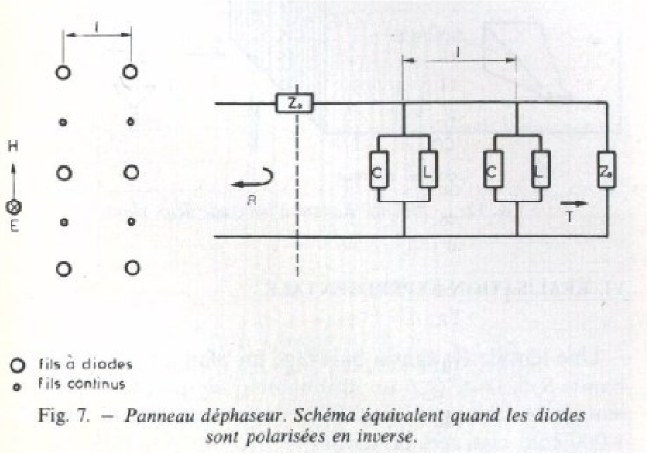
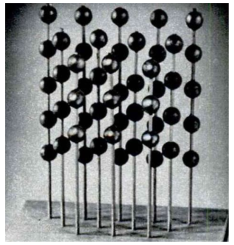
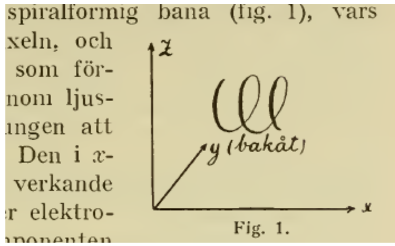
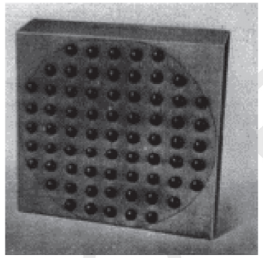


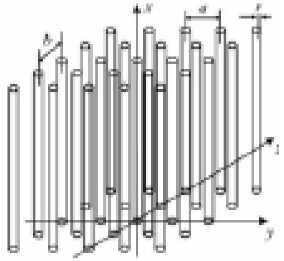
Fig. 7. – Panneau déphaseur. Schéma équivalent quand les diodes sont polarisées en inverse.

Chekroun, C., Herrick, D., Michel, Y.M., Pauchard, R., Vidal, P. (1979). Radant—New method of electric scanning. *L'Onde Electr.* 59 (89): 89–94.









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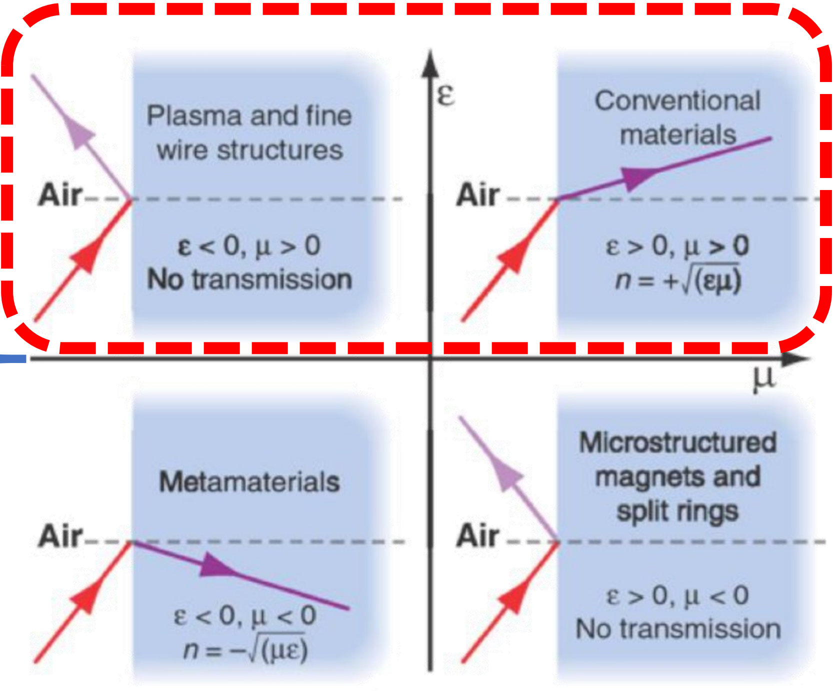
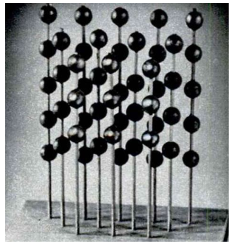
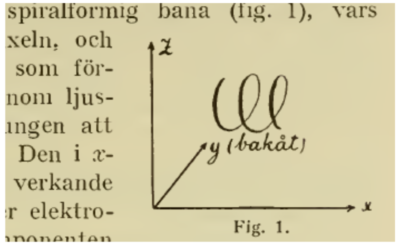
Artificial Dielectrics



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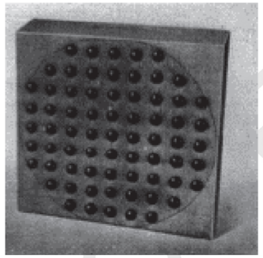
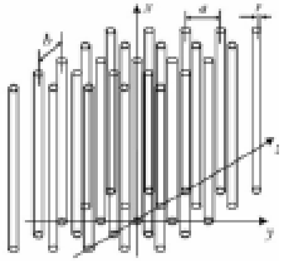
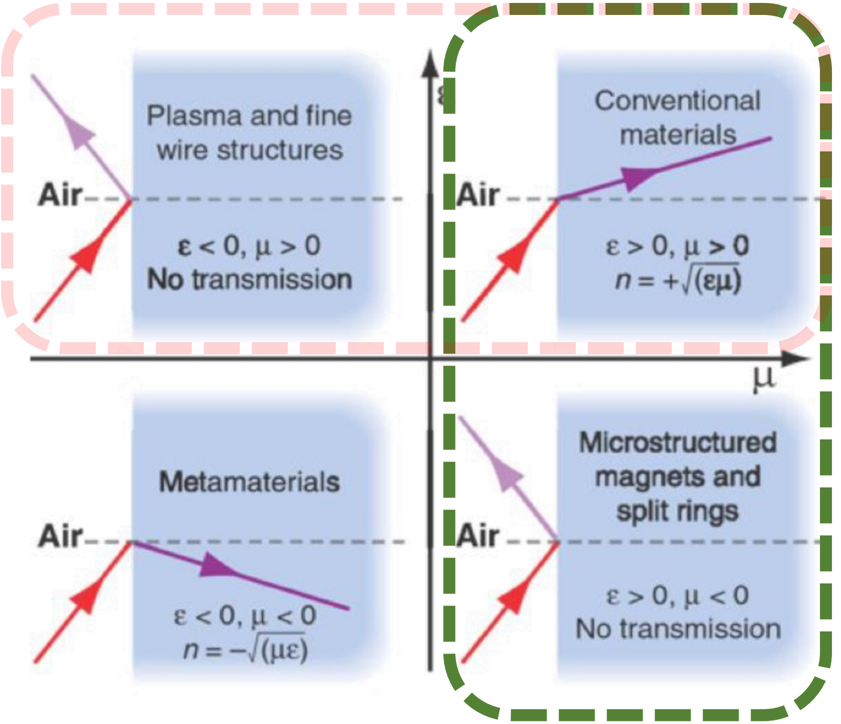




History: Effective media theory

Schelkunoff, S.A. and Friis, H.T. (1952). *Antennas: Theory and practice*. Wiley.



Hardy, W.N. and Whitehead, L.A. (1981). Split-ring resonator for use in magnetic resonance from 200–2000 MHz. *Rev. Sci. Instrum.* 52: 213–216.

Schneider, H.J. and Dullenkopf, P. (1977). Slotted tube resonator: a new NMR probe head at high observing frequencies. *Rev. Sci. Instrum.* 48: 68.

Pendry, J.B., Holden, A.J., Robbins, D.J., and Stewart, W.J. (1999). Magnetism from conductors and enhanced nonlinear phenomena. *IEEE Trans. Microwave Theory Tech.* 47: 2075–2084.

Baena, J.D., Marques, R., Medina, F., and Martel, J. (2004). Artificial magnetic metamaterial design by using spiral resonators. *Phys. Rev. B* 69: 014402

History: Effective Media

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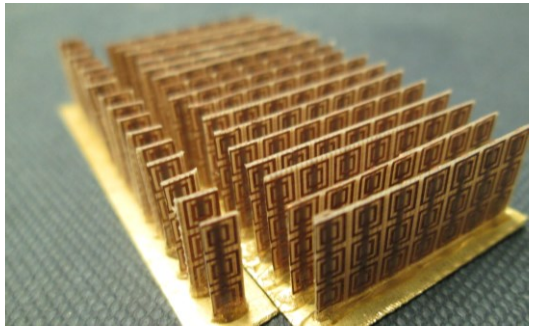

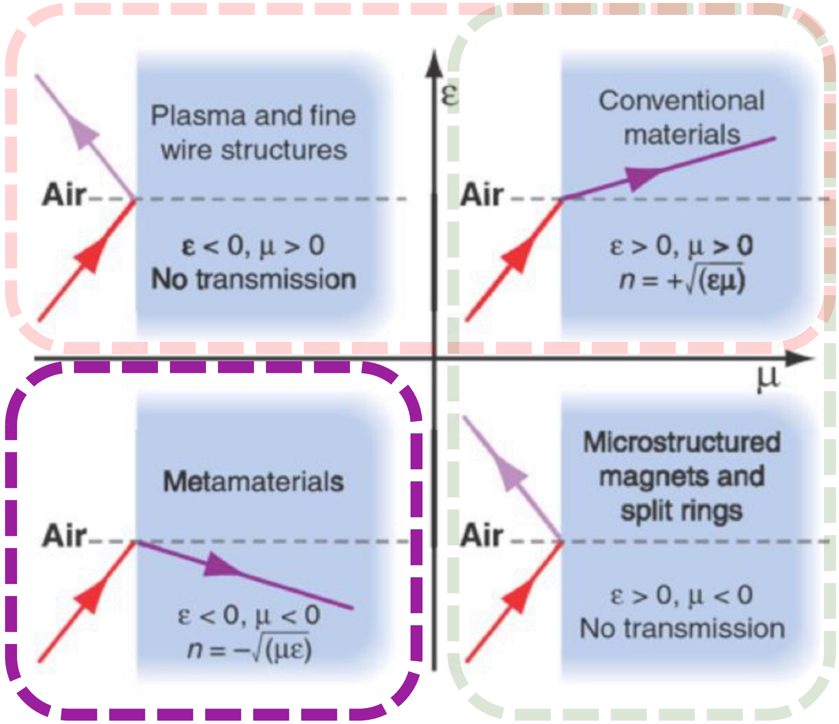

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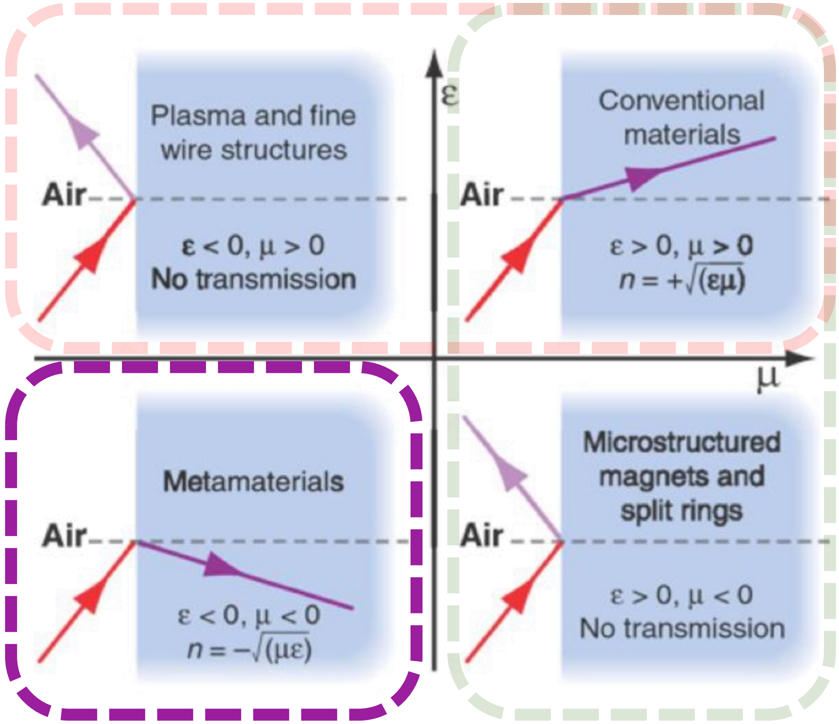
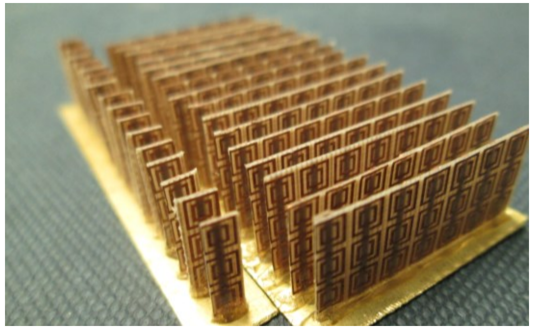


Metamaterial coined by Rodger Walser in 1999, *" . . . macroscopic composites having man-made, three-dimensional, periodic cellular architecture designed to produce an optimized combination, not available in nature, of two or more responses to specific excitation."*



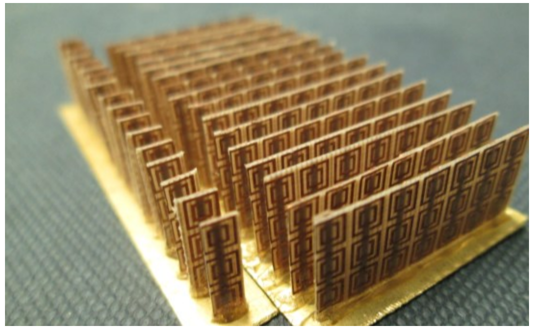
$$n' = \pm \frac{1}{kd} \Re \left[cos^{-1} \left(\frac{1 - S_{11}^2 + S_{21}^2}{2S_{11}^2} \right) \right] + \frac{2\pi m}{kd}$$

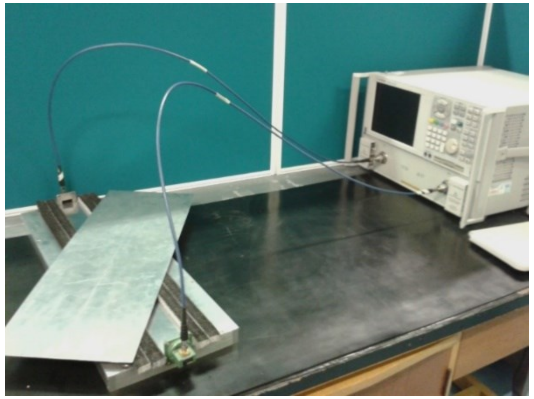
$$n'' = \pm \frac{1}{kd} \Im \left[cos^{-1} \left(\frac{1 - S_{11}^2 + S_{21}^2}{2S_{11}^2} \right) \right]$$

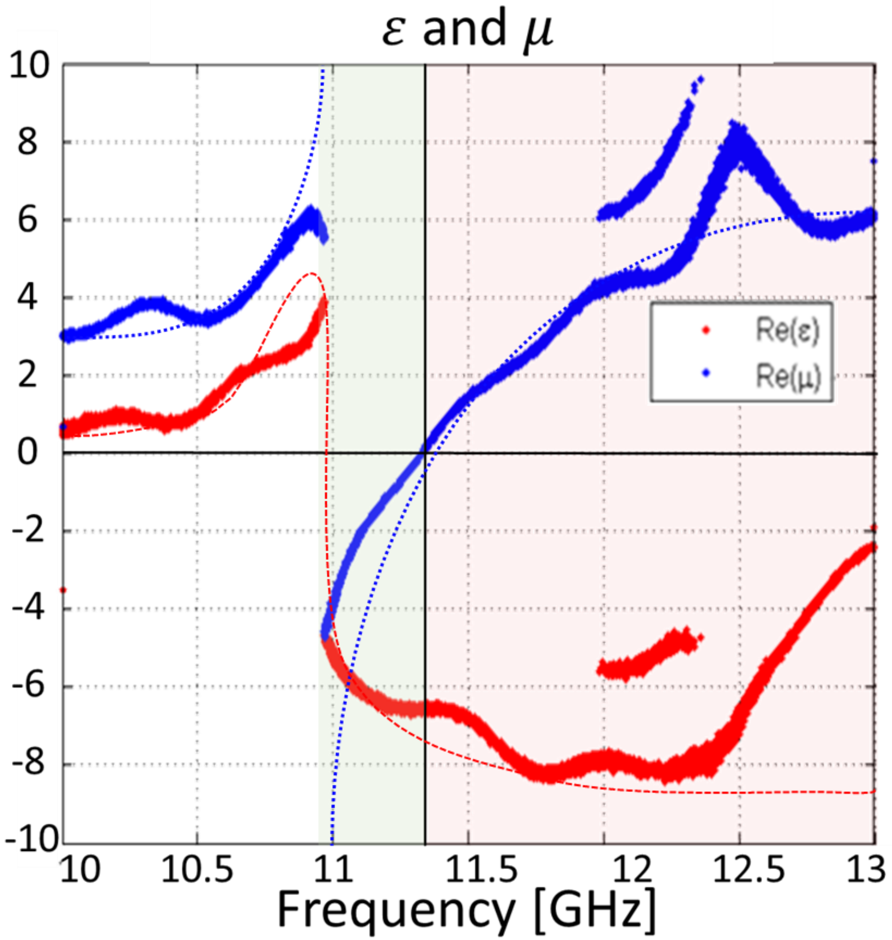
$$Z = \pm \left[\frac{(1 + S_{11})^2 - S_{21}^2}{(1 - S_{11})^2 - S_{21}^2} \right]^{\frac{1}{2}}$$

$$\epsilon = n/Z$$
$$\mu = nZ$$

Nicolson, Ross (1970). ieee transactions instrumentation and measurement, 19 (4), 337-382

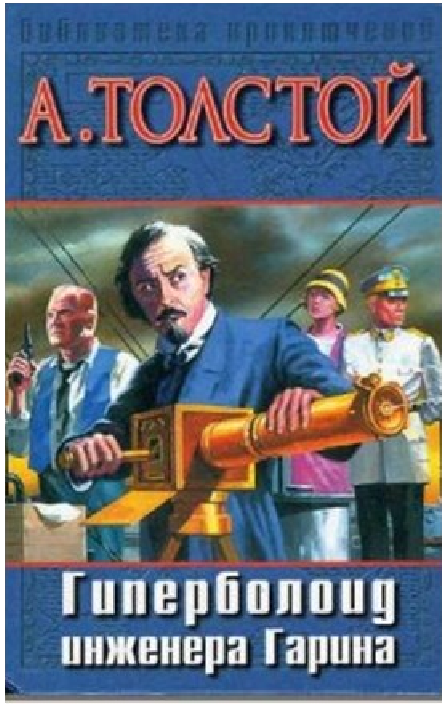




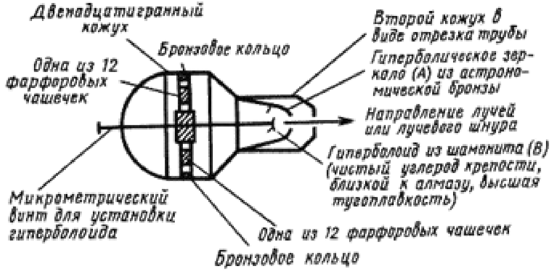


Artificial EM Material Mediated Amplification

Engineer Garin's Hyperboloid



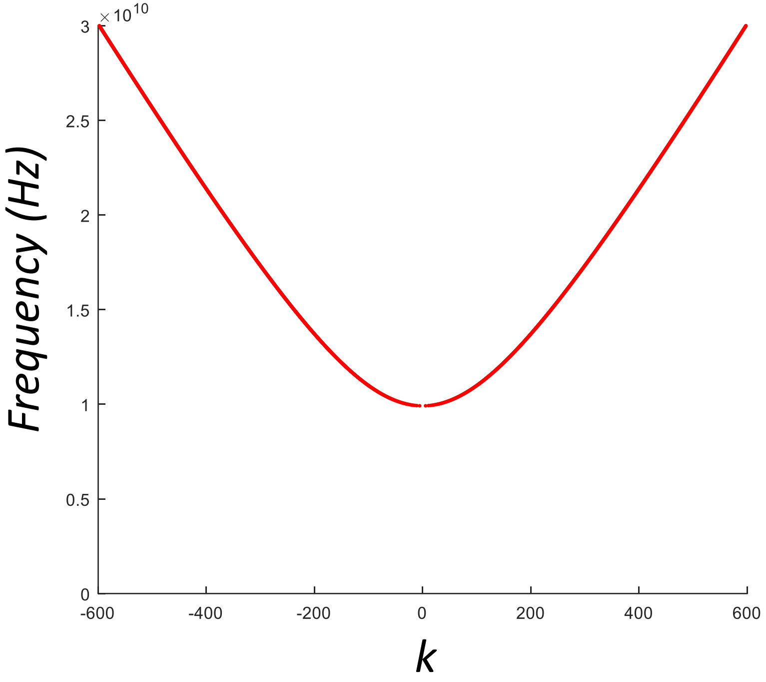
Tolstoy (1914)



Artificial EM Material Mediated Amplification

Artificial EM Material Mediated Amplification

$$\beta_0 = c^{-1}\sqrt{\omega^2 - \omega_c^2}$$



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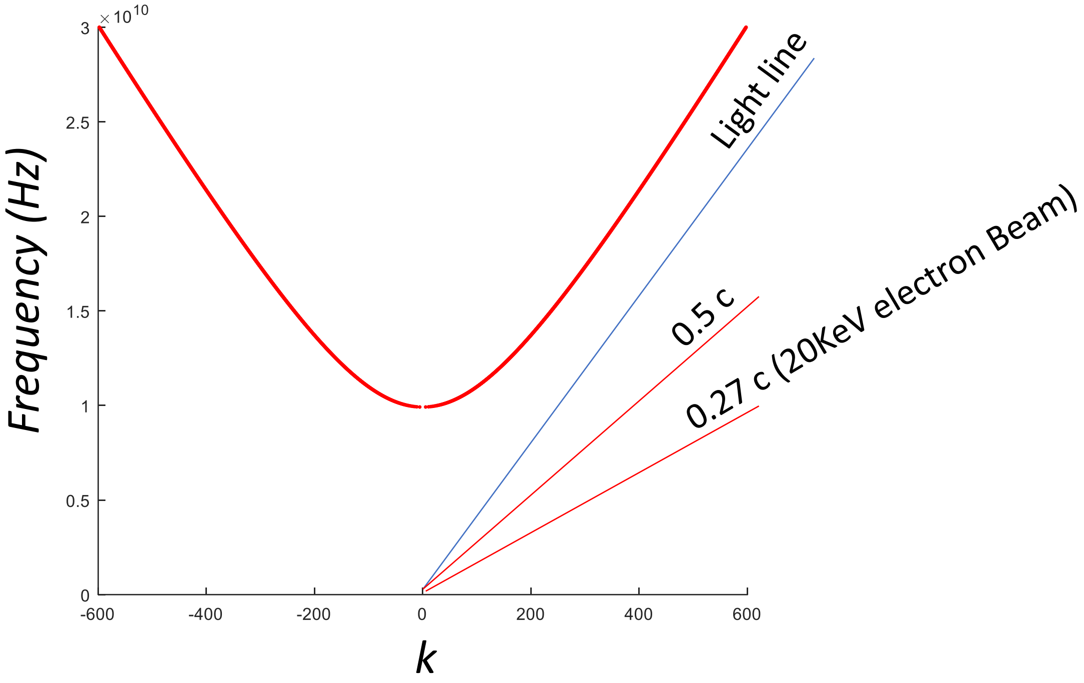


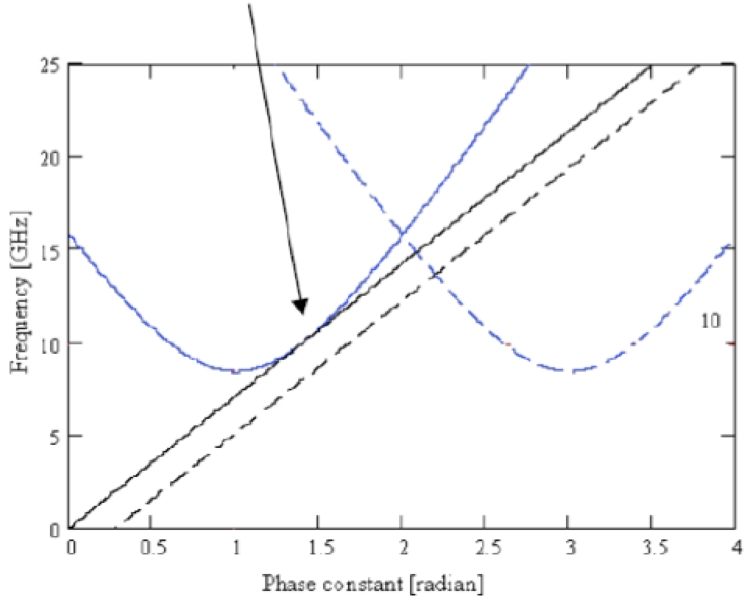
Artificial EM Material Mediated Amplification

Spatial Harmonics Wave Components parallel to the beam.
The SHWC interact with the beam resulting in energy

By a superposition of the spatial harmonics the field parallel to the beam can be expressed by Floquets theorem

$$\vec{E}(z) = \sum_{m=-\infty}^{\infty} \vec{E}_m(x,y)e^{-i\beta_m z}, \beta_m = \beta + \frac{2m\pi}{p}$$

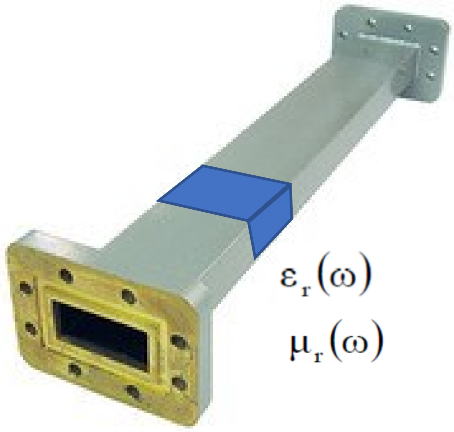
Single synchronism frequency point



$$\beta = \beta_0\left(1 + \frac{h}{p}\right) + \frac{\pi}{p} = \omega t = \omega(p/v_e)$$

$$\beta_0 = c^{-1}\sqrt{\omega^2 - \omega_c^2}$$

Artificial EM Material Mediated Amplification



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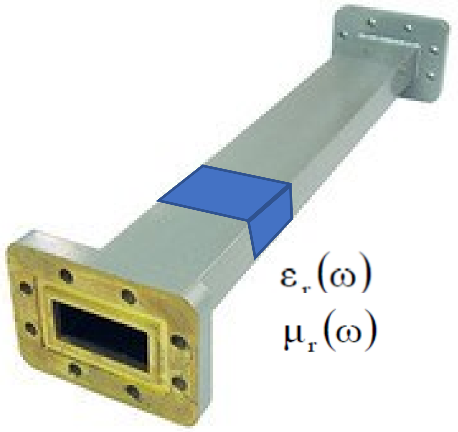
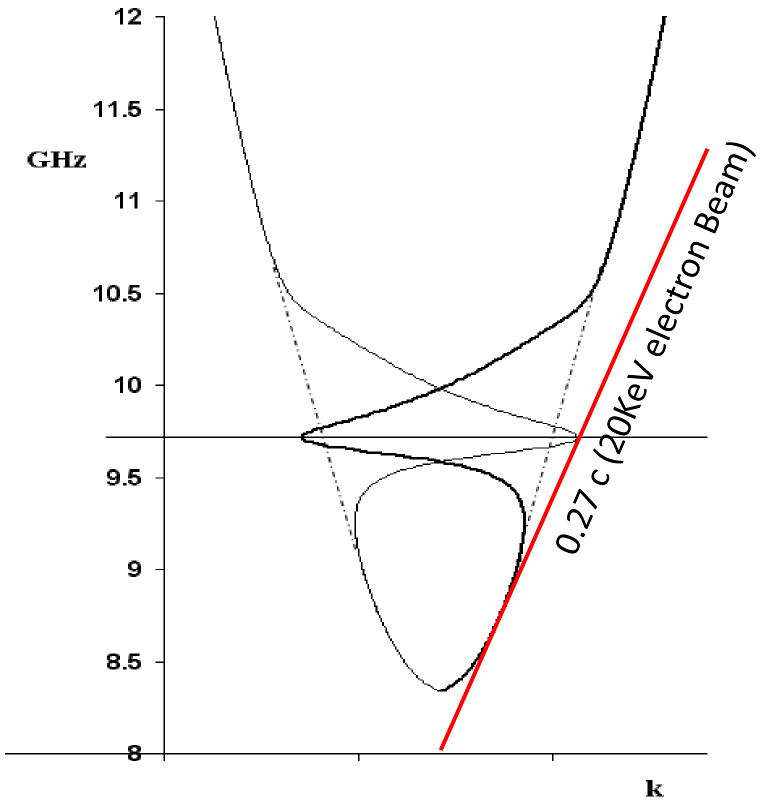


$$\beta_{mm}(\omega) = c^{-1}\sqrt{\omega^2\epsilon_r(\omega)\mu_r(\omega) - \omega_c^2}$$



Artificial EM Material Mediated Amplification

Madey's Theory

$$m_0 c^2 \frac{d}{dt}\gamma = -e\mathbf{E}v$$ Lorentz's Force

$$\vec{E}(z) = \sum_{m=-\infty}^{\infty} \vec{E}_m(x,y) e^{-i\beta_m z}$$

1st order perturbation >> Spontaneous emission

$$m_0 c^2 \frac{d}{dt}\gamma_1 = -e\mathbf{E}v_0$$

2nd order perturbation >> Stimulated emission

$$\langle \Delta\gamma_2 \rangle = \frac{1}{2}\frac{d}{d\gamma}\langle \Delta\gamma_1{}^2 \rangle$$

Artificial EM Material Mediated Amplification

Madey's Theory

$$m_0 c^2 \frac{d}{dt}\gamma = -e\mathbf{E}v$$ Lorentz's Force

1st order perturbation >> Spontaneous emission

$$m_0 c^2 \frac{d}{dt}\gamma_1 = -e\mathbf{E}v_0$$

2nd order perturbation >> Stimulated emission

$$\langle \Delta\gamma_2 \rangle = \frac{1}{2}\frac{d}{d\gamma}\langle \Delta\gamma_1{}^2 \rangle$$

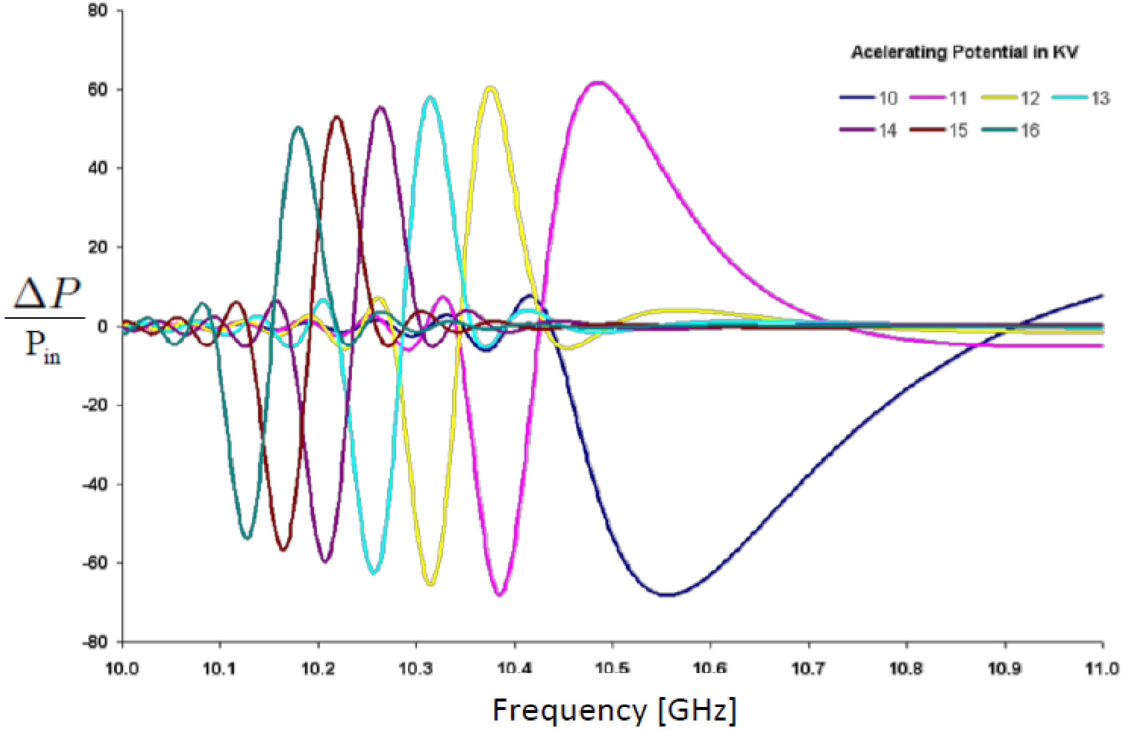
$$\frac{\Delta P_{out}}{P_{in}} = \frac{-\frac{1}{2}\frac{d}{d\gamma}\langle \Delta\gamma_1{}^2 \rangle m_0 c^2 \frac{I}{e}}{P_{in}}$$

$$\Delta P = \frac{\omega^2 \mu}{\beta_0}\frac{L^3}{2ab} Z^2 \frac{d}{dX}\left(\frac{\sin^2(X)}{X^2}\right)\frac{c}{\gamma^3}\frac{1}{v_e^3}\left(mc^2 I_b/e\right)$$

$$Z = \frac{e}{mc^2}\frac{b}{p}\mathrm{sinc}\left(\beta_n'\frac{b}{2}\right)$$
$$\gamma = 1 + V_{acc}/\left(m_0 c^2\right)$$
$$X = \left(\frac{\omega}{v_e} - \beta_n'\right)\frac{L}{2}$$

Tan & Seviour, Europhys.Lett.87:34005,2009

Artificial EM Material Mediated Amplification



$$\frac{\Delta P_{out}}{P_{in}} = \frac{-\frac{1}{2}\frac{d}{d\gamma}\langle \Delta\gamma_1{}^2 \rangle m_0 c^2 \frac{I}{e}}{P_{in}}$$

$$\Delta P = \frac{\omega^2 \mu}{\beta_0}\frac{L^3}{2ab} Z^2 \frac{d}{dX}\left(\frac{\sin^2(X)}{X^2}\right)\frac{c}{\gamma^3}\frac{1}{v_e^3}\left(mc^2 I_b/e\right)$$

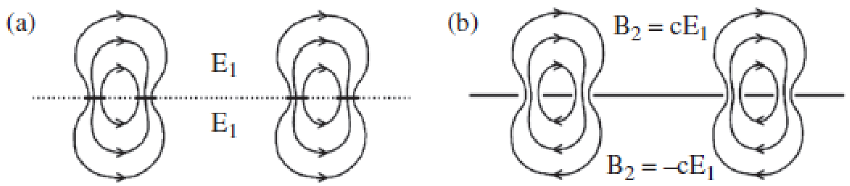
$$Z = \frac{e}{mc^2}\frac{b}{p}\mathrm{sinc}\left(\beta_n' \frac{b}{2}\right)$$
$$\gamma = 1 + V_{acc}/\left(m_0 c^2\right)$$
$$X = \left(\frac{\omega}{v_e} - \beta_n'\right)\frac{L}{2}$$

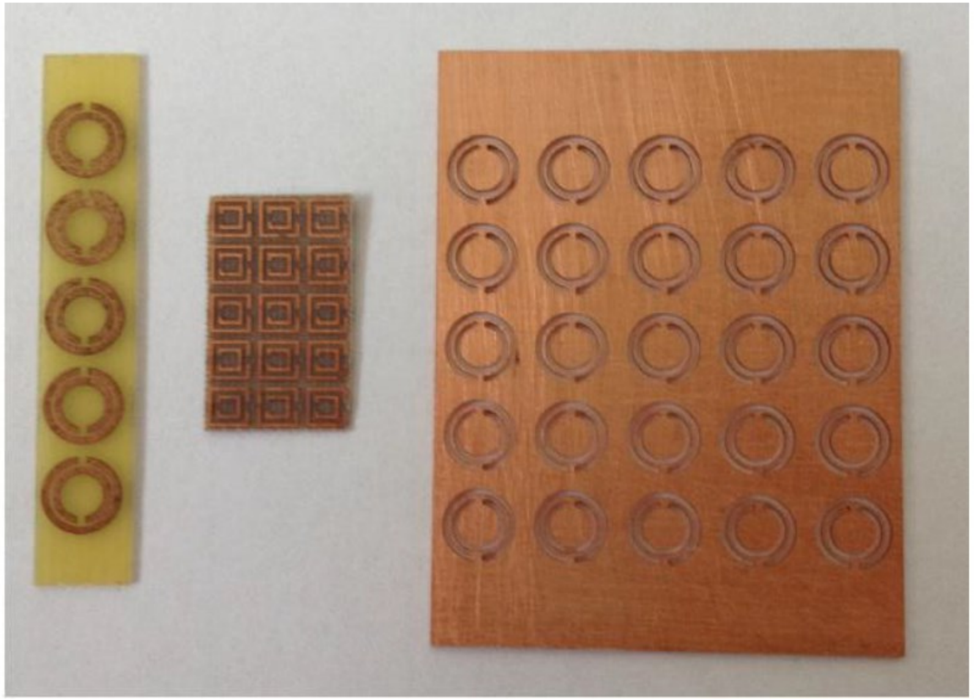
X determined by wave/beam velocity,

X > 0 $\quad v_{beam} < v_g$

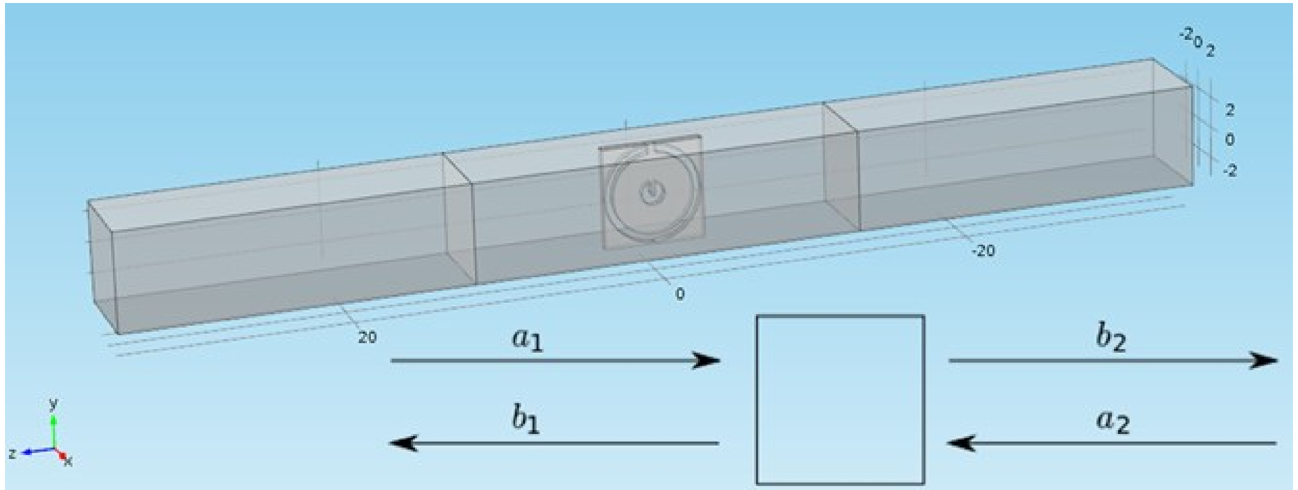
Tan & Seviour, Europhys.Lett.87:34005,2009

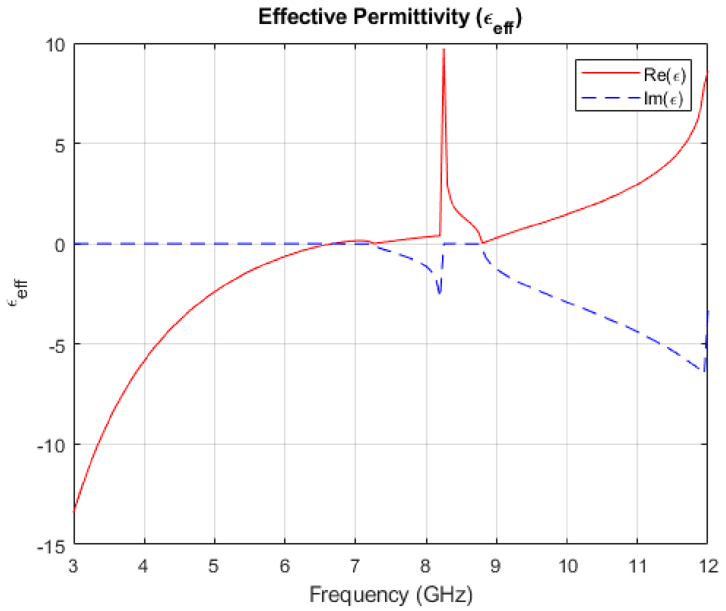
Artificial EM Material Mediated EM Wave Generation & Amplification

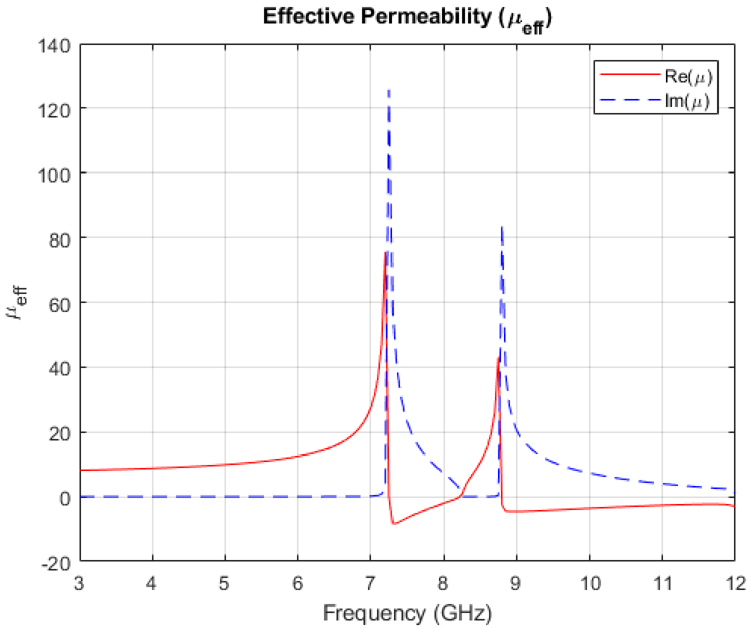


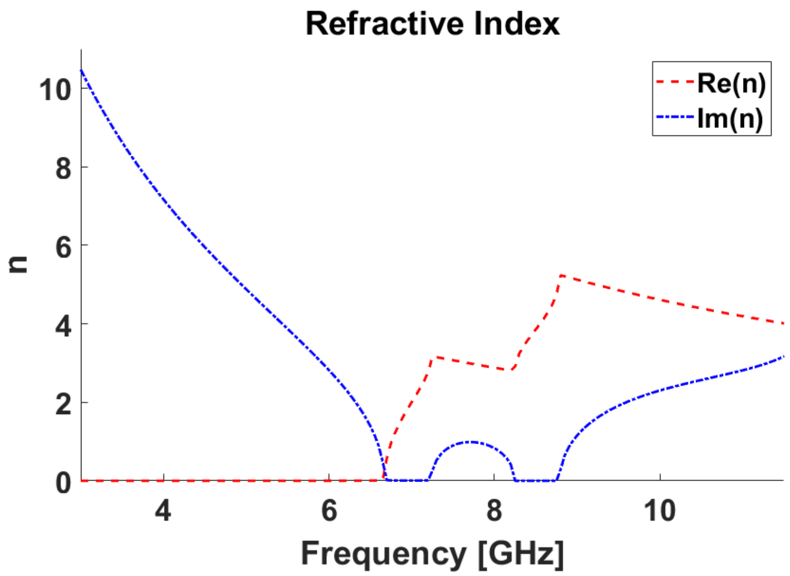


Artificial EM Material Mediated EM Wave Generation

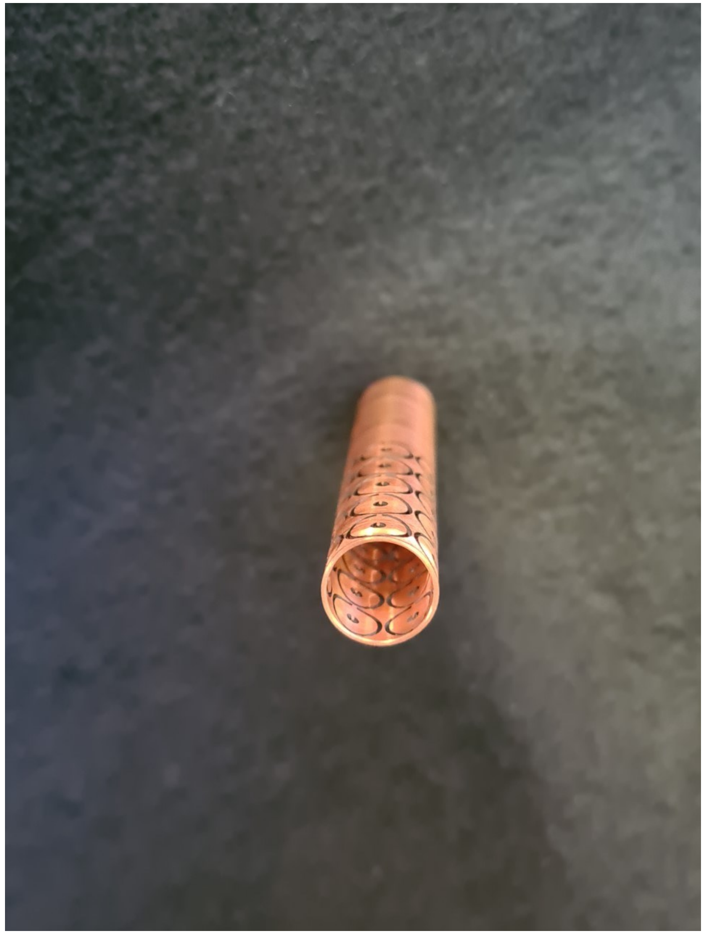


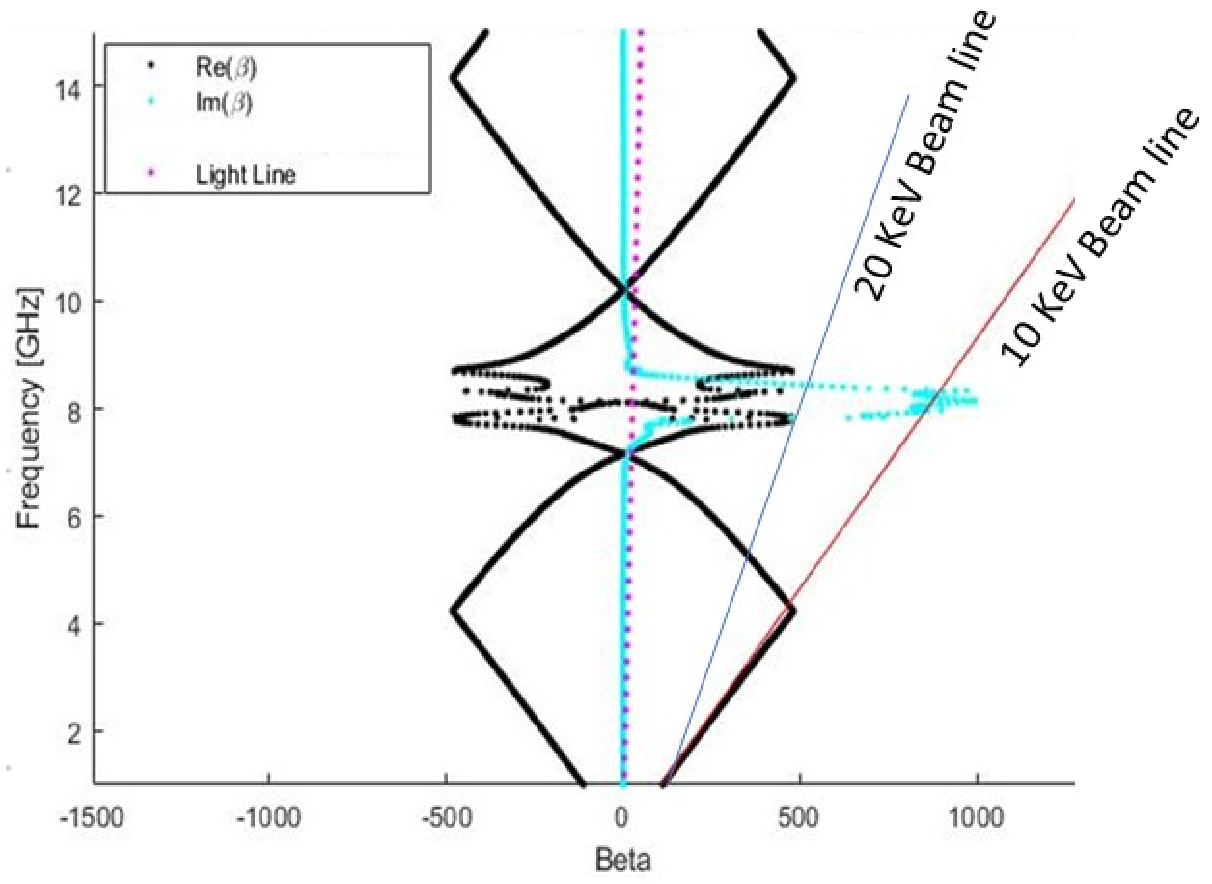




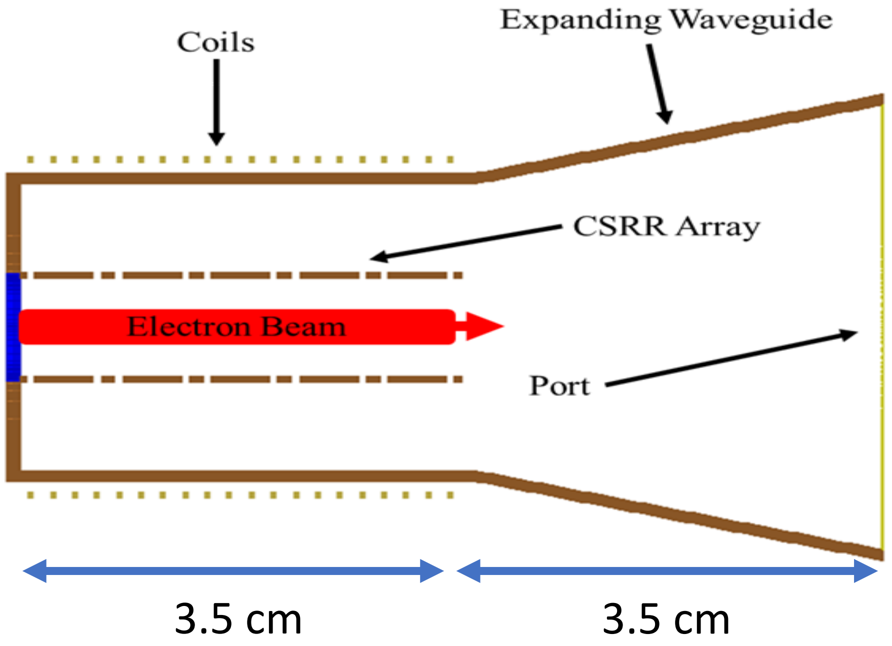


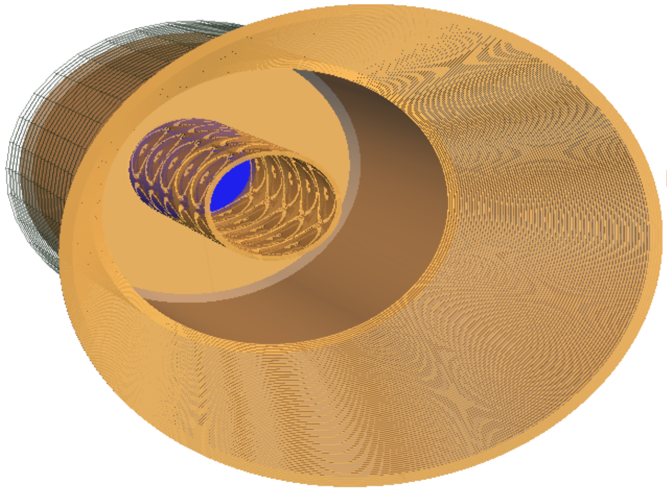

TEN PENCE
10

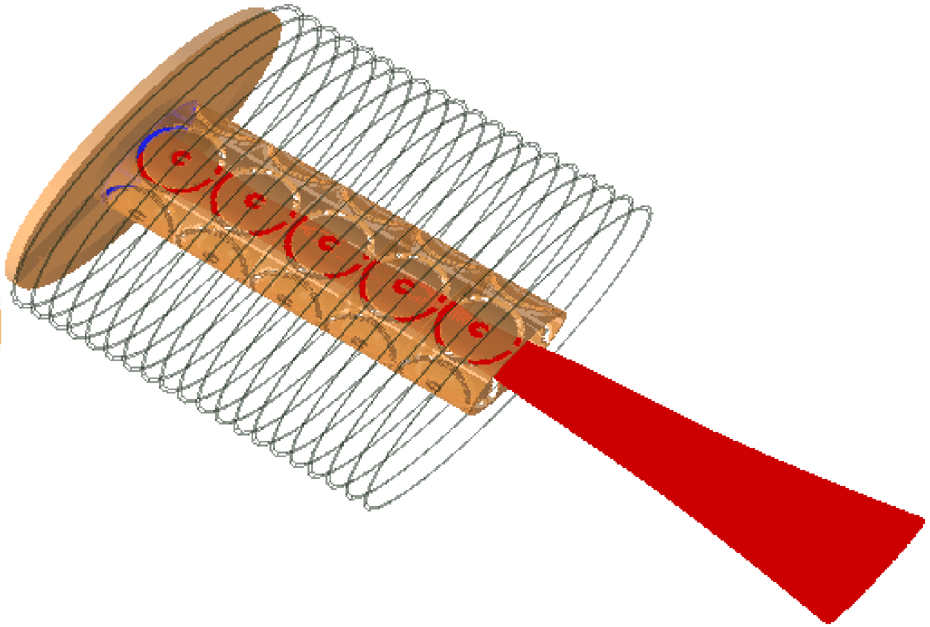



Re(β)
Im(β)
Light Line
20 KeV Beam line
10 KeV Beam line
Frequency [GHz]
Beta
14
12
10
8
6
4
2
-1500
-1000
-500
0
500
1000

Artificial EM Material Mediated EM Wave Generation

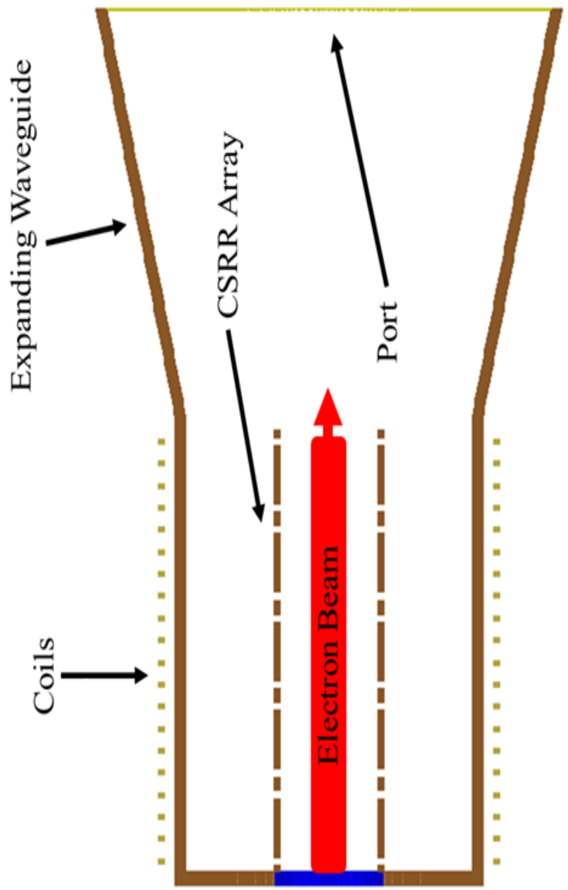


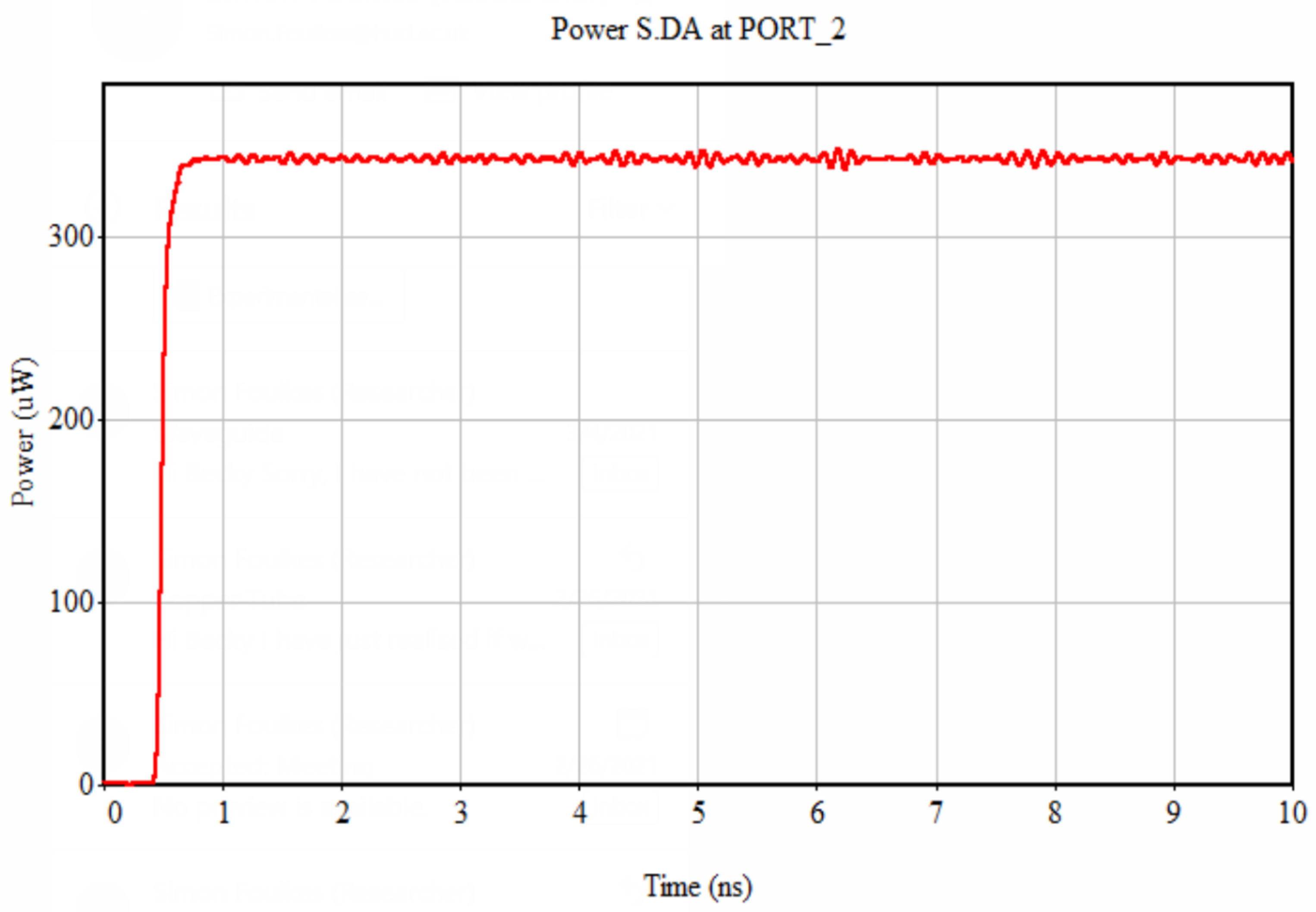




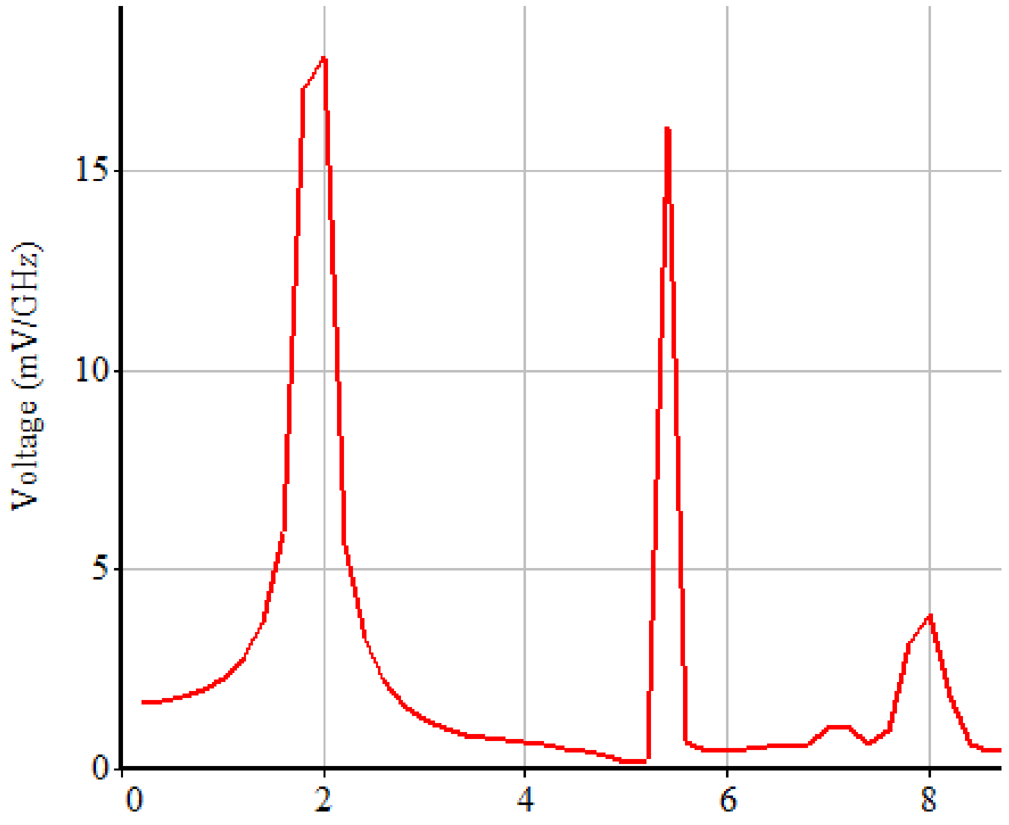
Artificial EM Material Mediated EM Wave Generation

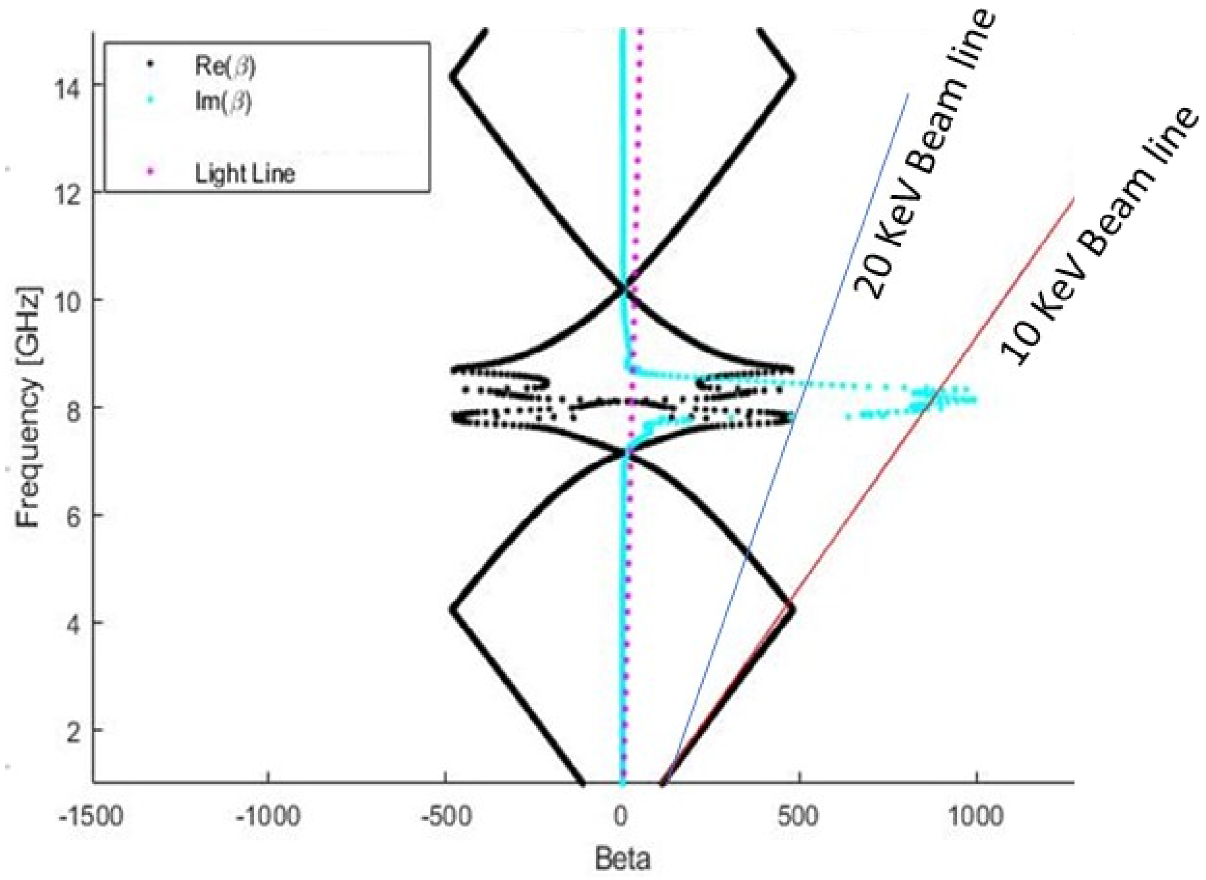
FDTD Particle-in-cell simulation to simulate electron (macro-particles) motion and interaction with our material

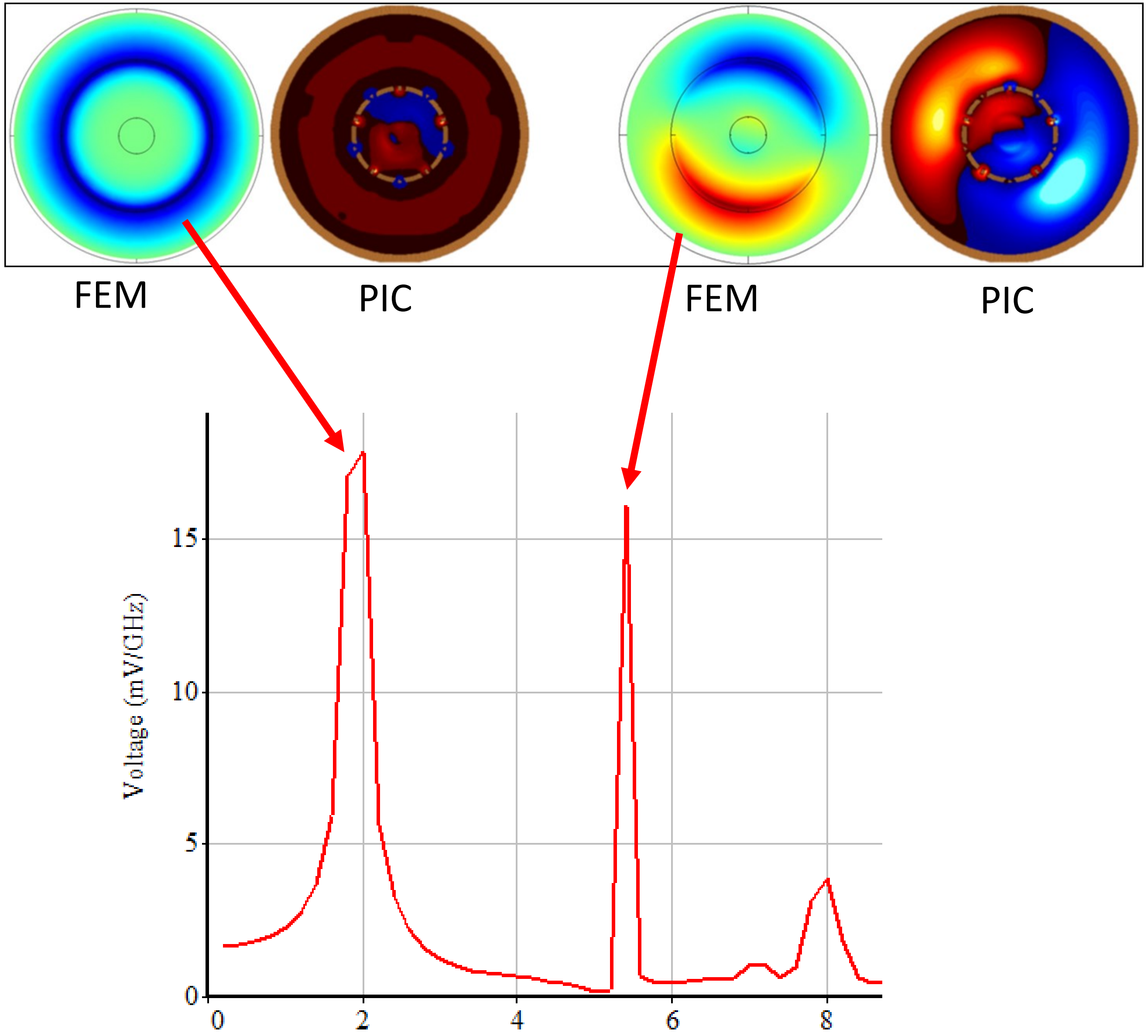


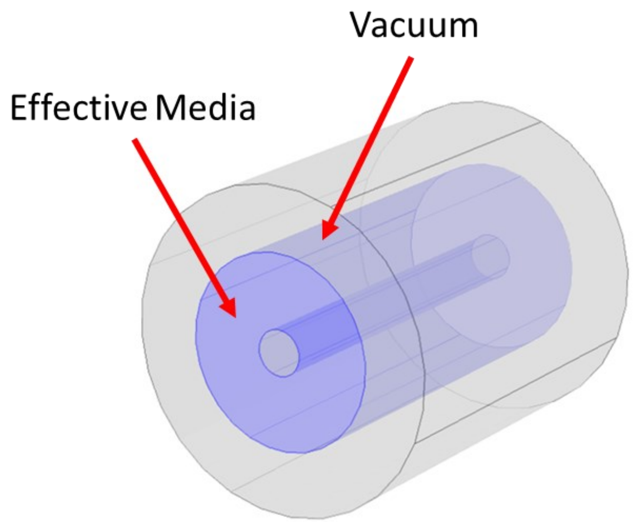


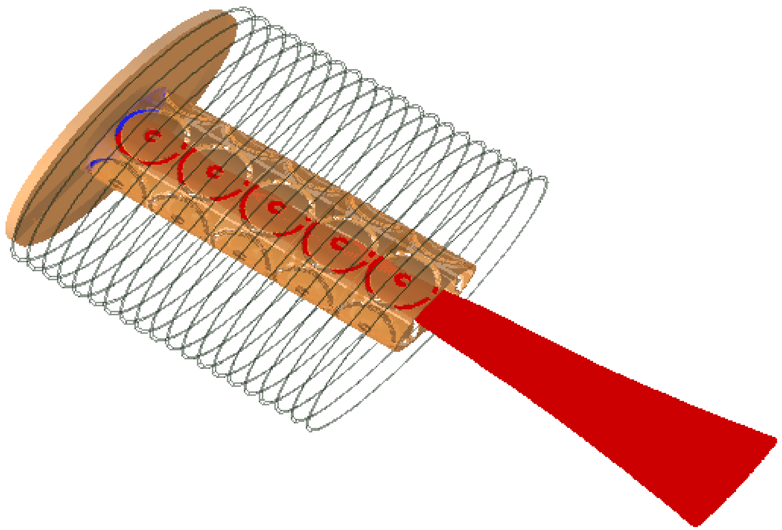
e-Beam
200 µA
20 KeV
4W

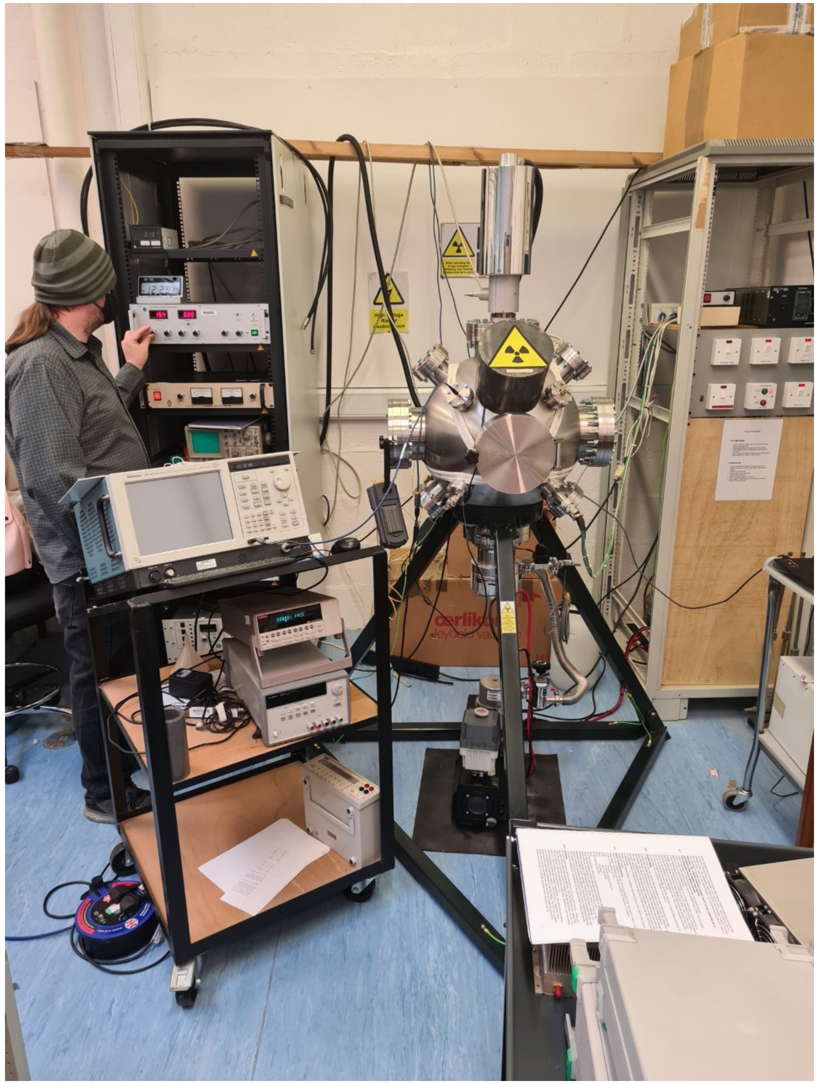

Voltage (mV/GHz)
15
10
5
0
0
2
4
6
8

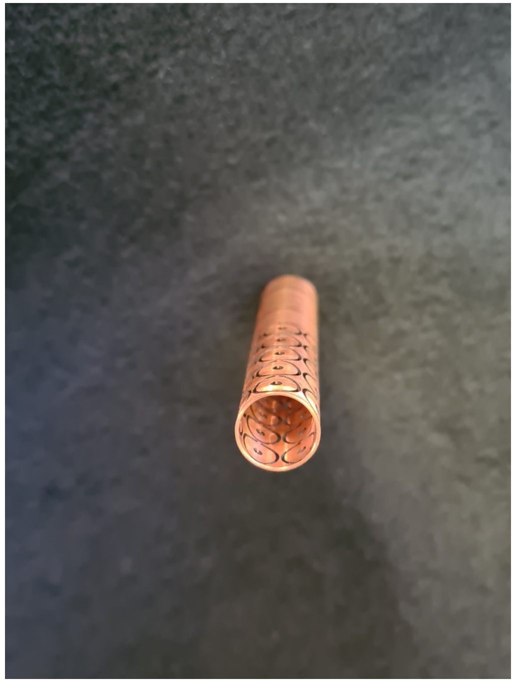

Re(β)
Im(β)
Light Line
20 KeV Beam line
10 KeV Beam line
Frequency [GHz]
14
12
10
8
6
4
2
-1500
-1000
-500
0
500
1000
Beta

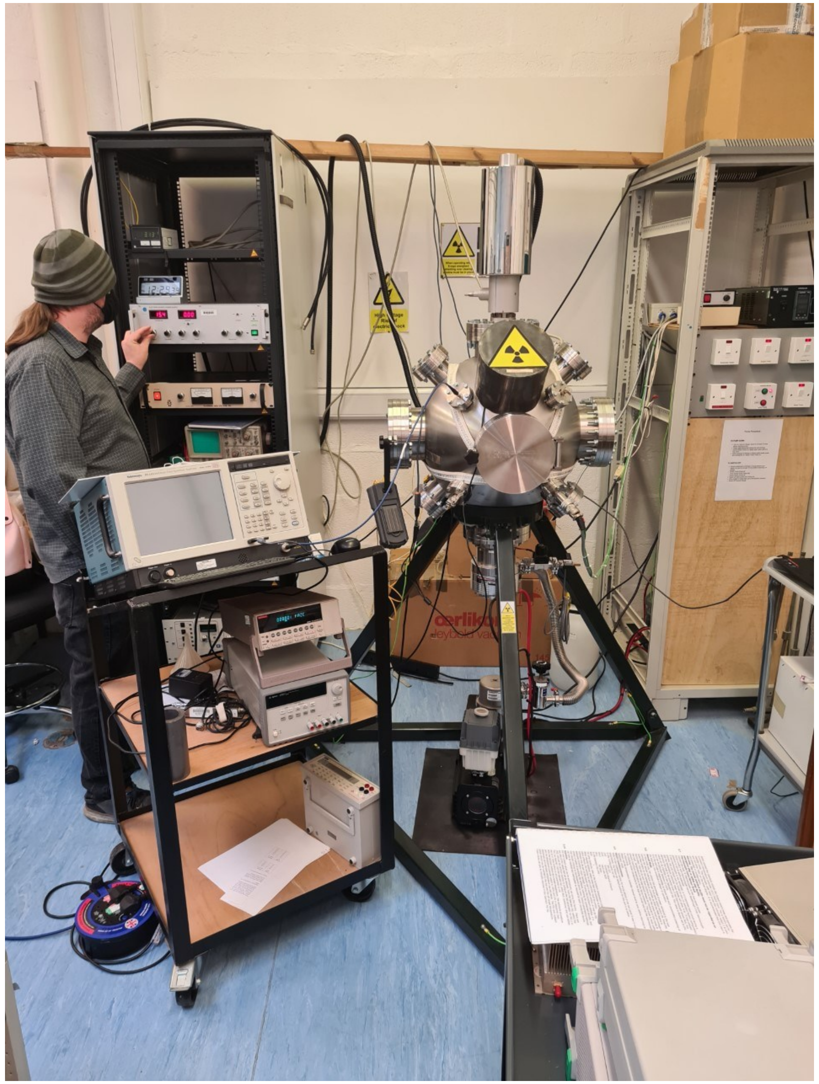

FEM
PIC
FEM
PIC
Voltage (mV/GHz)
0
5
10
15
0
2
4
6
8


Vacuum
Effective Media

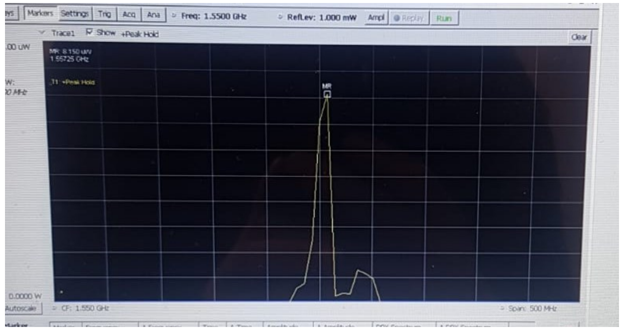




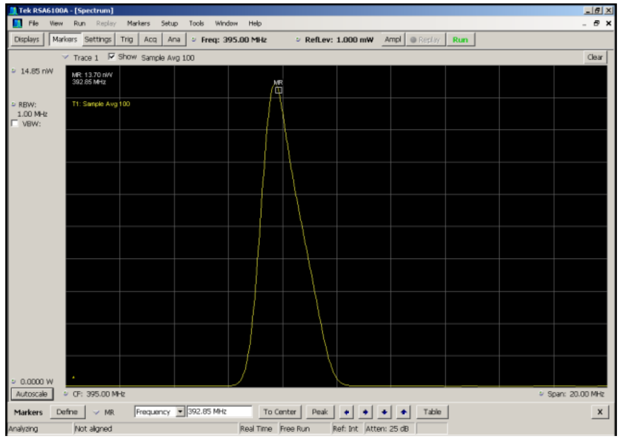


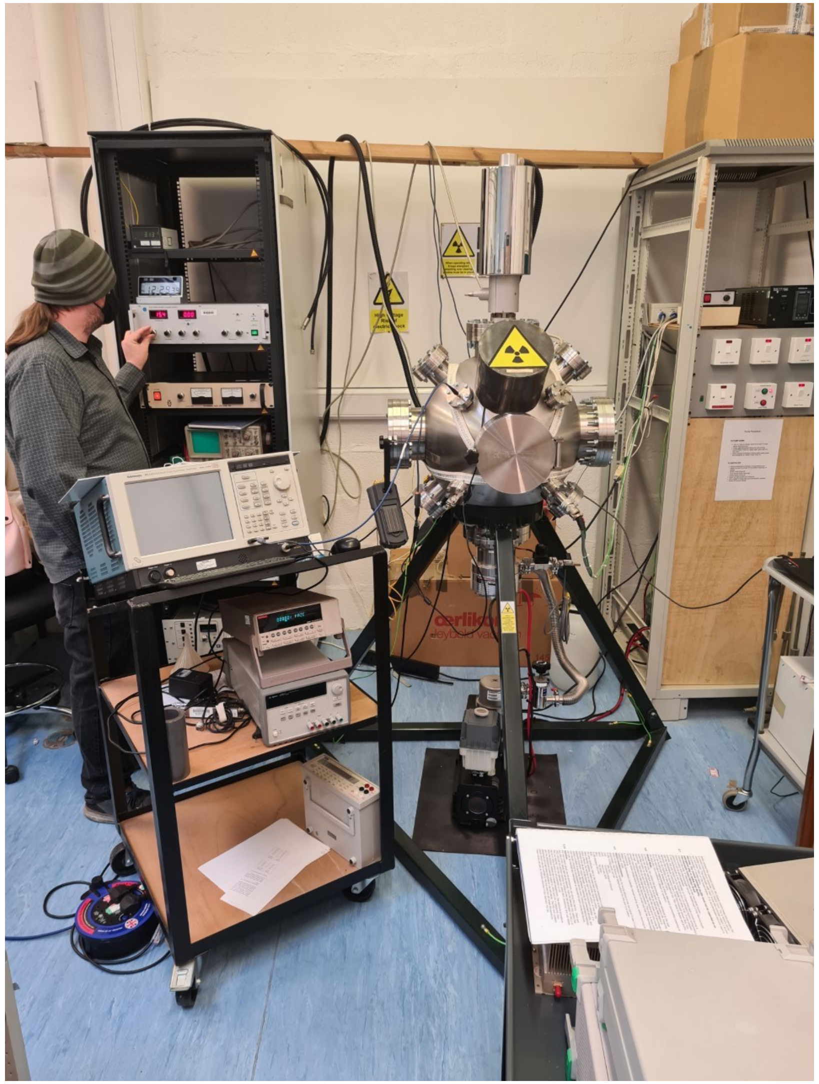


1.5 GHz signal

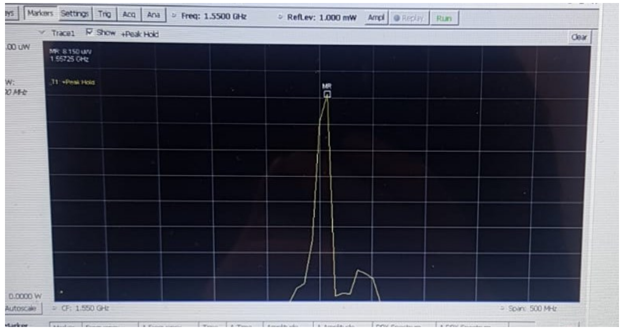


392 MHz signal

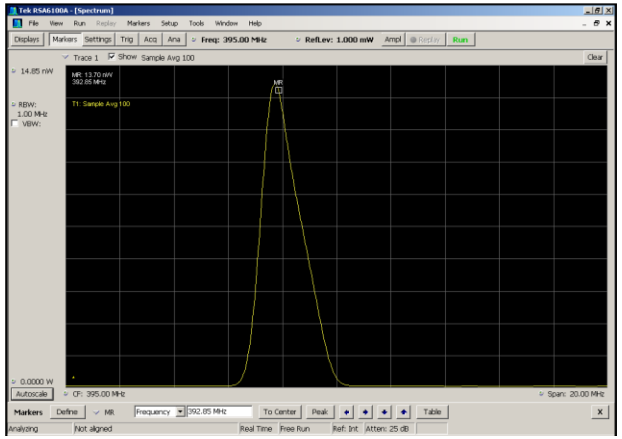


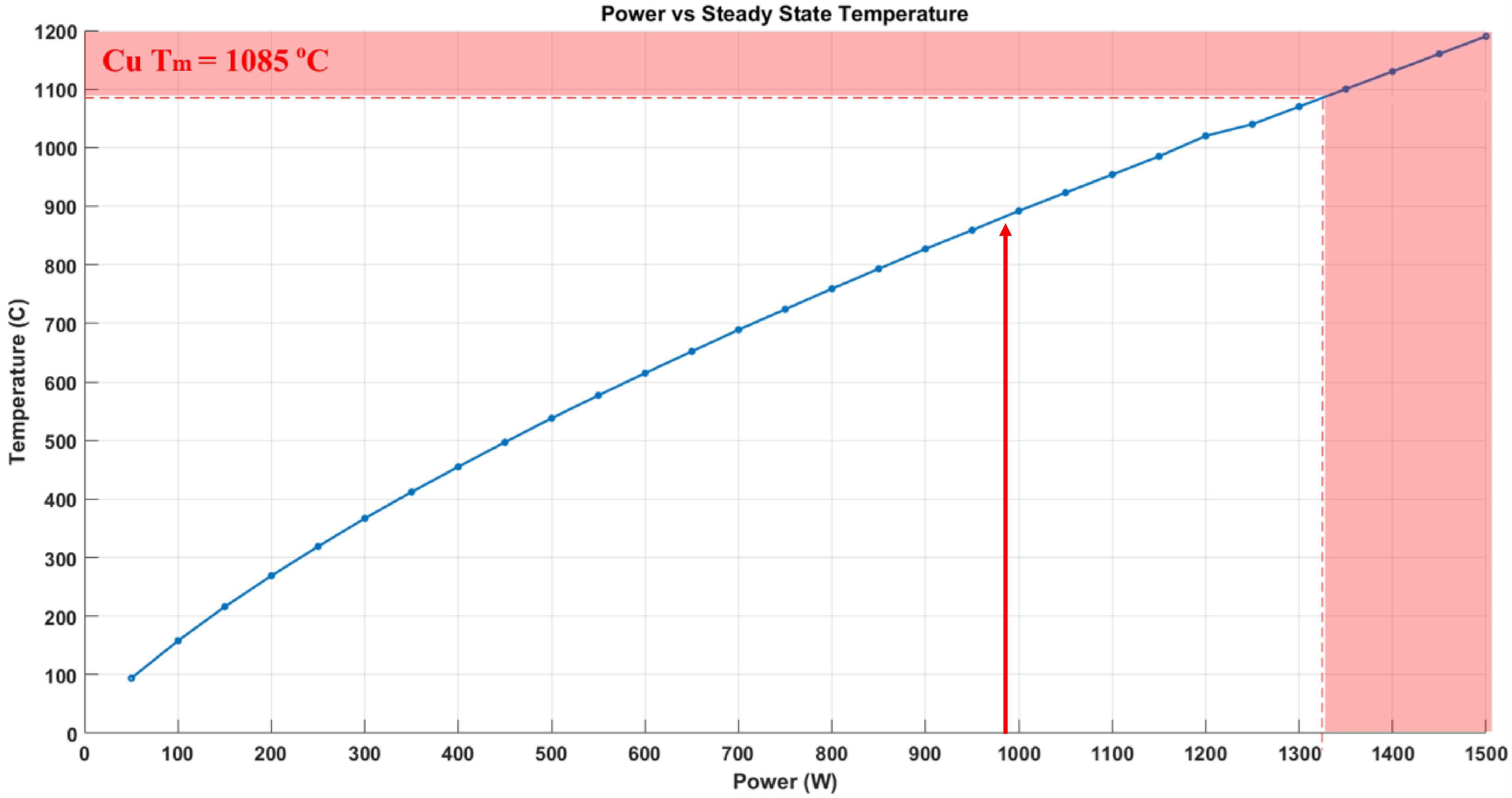


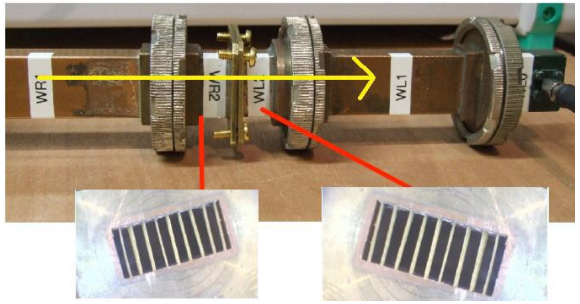
1.5 GHz signal

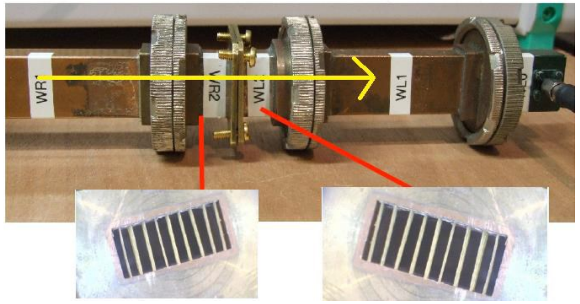


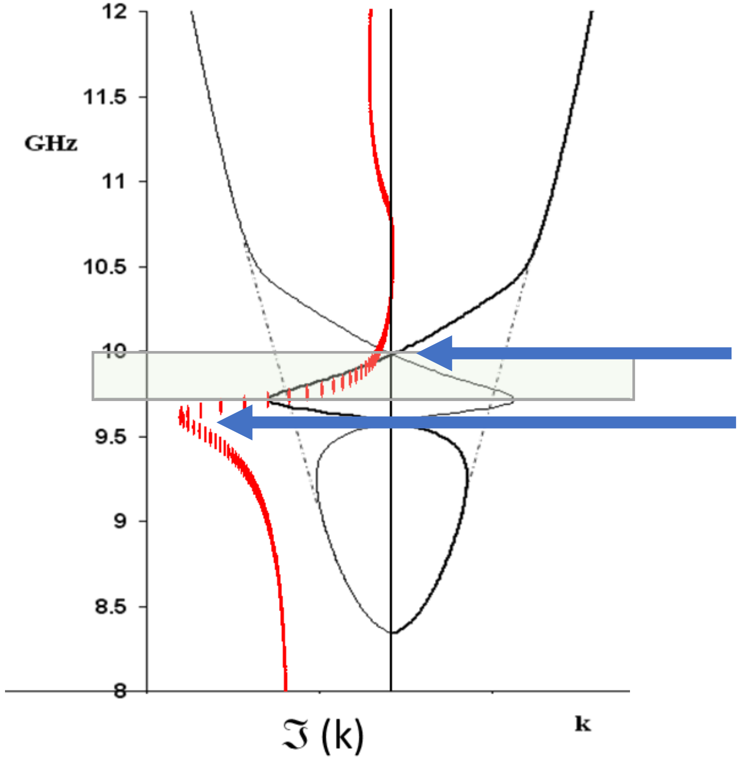
392 MHz signal



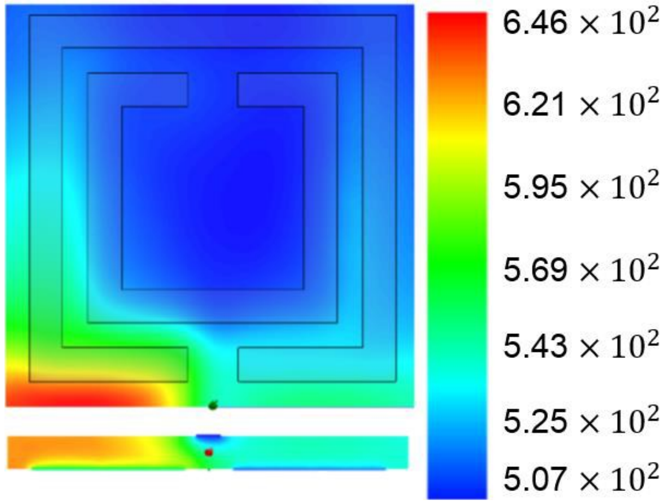

Power vs Steady State Temperature
Cu Tm = 1085 °C
Temperature (C)
Power (W)
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500

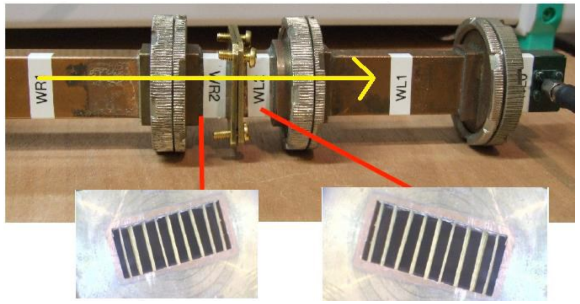

WR1
WR2
WL2
WL1

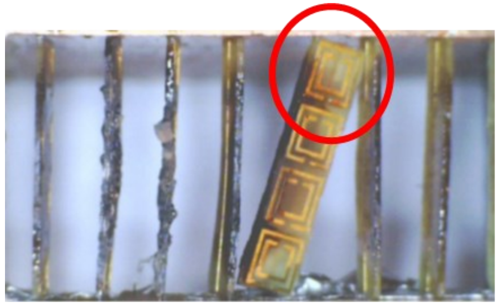

WR1
WR2
WL
WL1


12
11.5
GHz
11
10.5
10
9.5
9
8.5
8
ℑ (k)
k

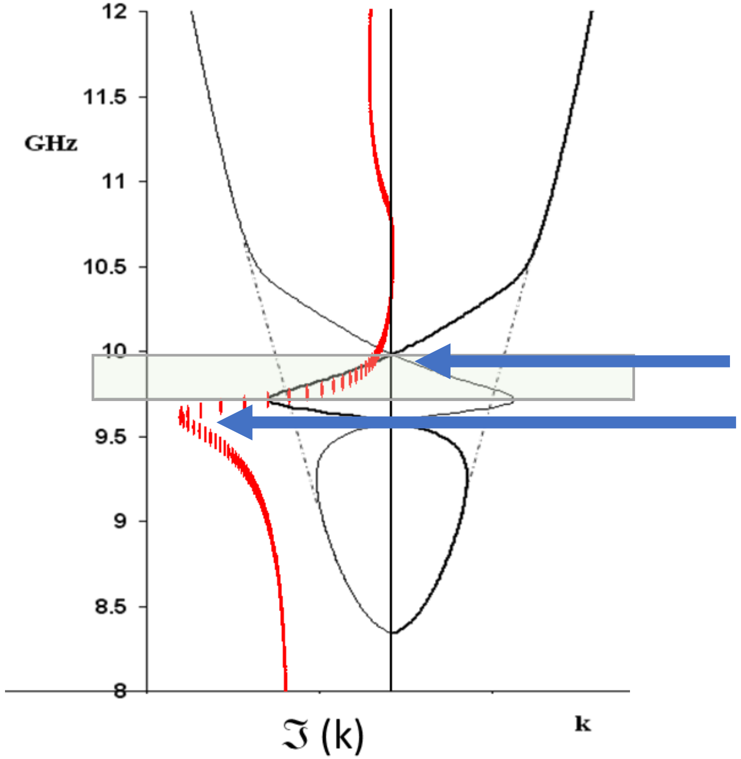
1W @ 10GHZ

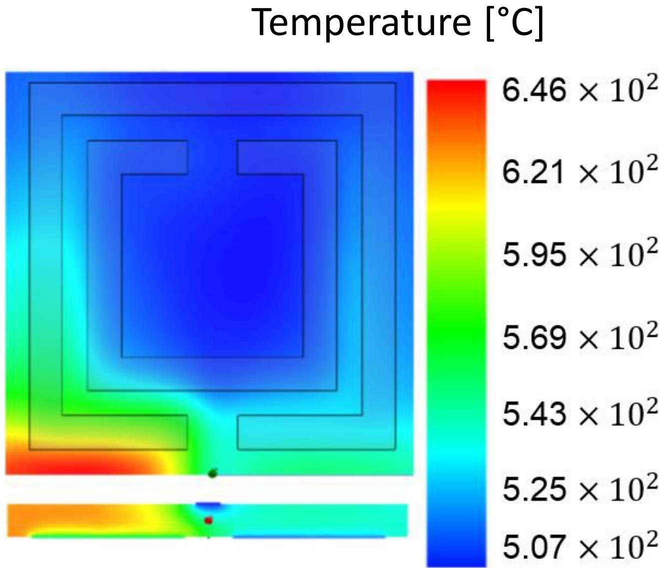

6.46×10^2
6.21×10^2
5.95×10^2
5.69×10^2
5.43×10^2
5.25×10^2
5.07×10^2

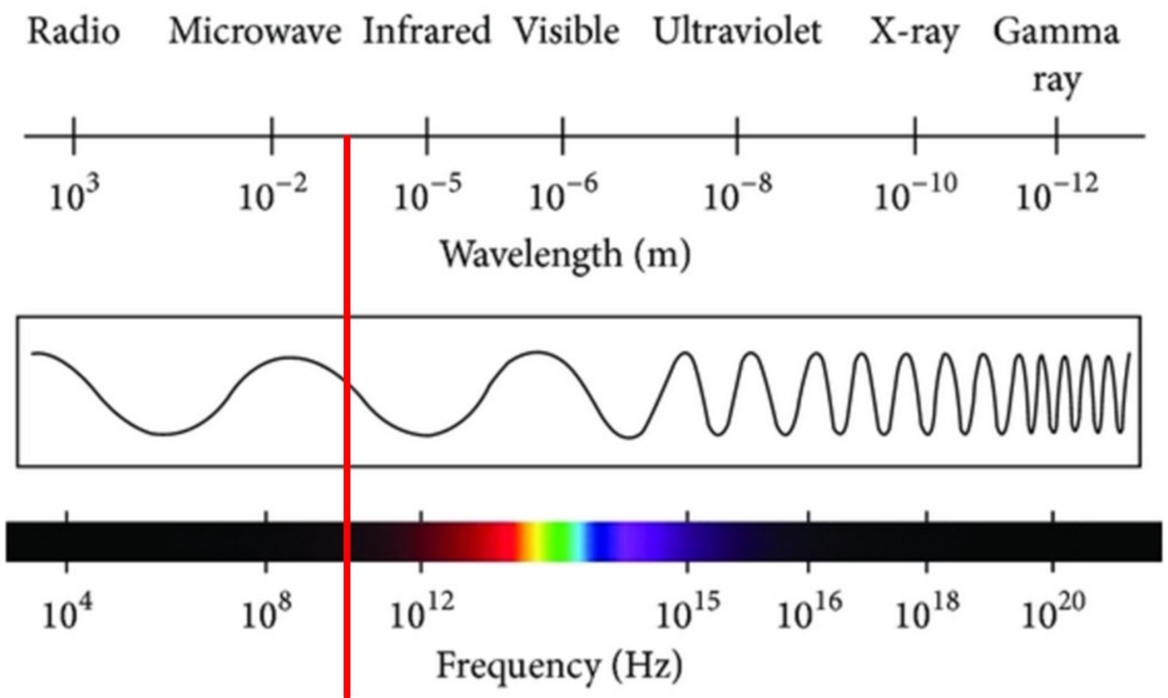

WR1
WR2
WL
WL1



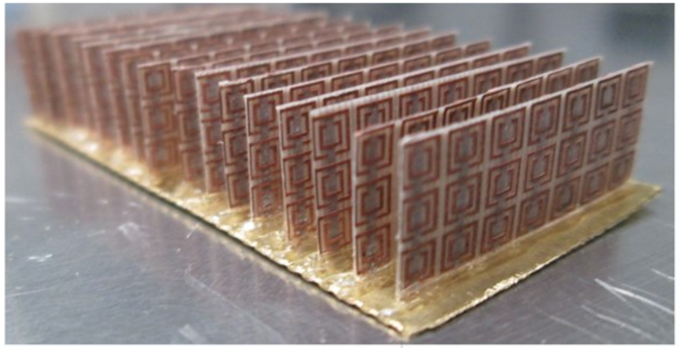

SRR after 1W @ 10GHZ for 15 secs

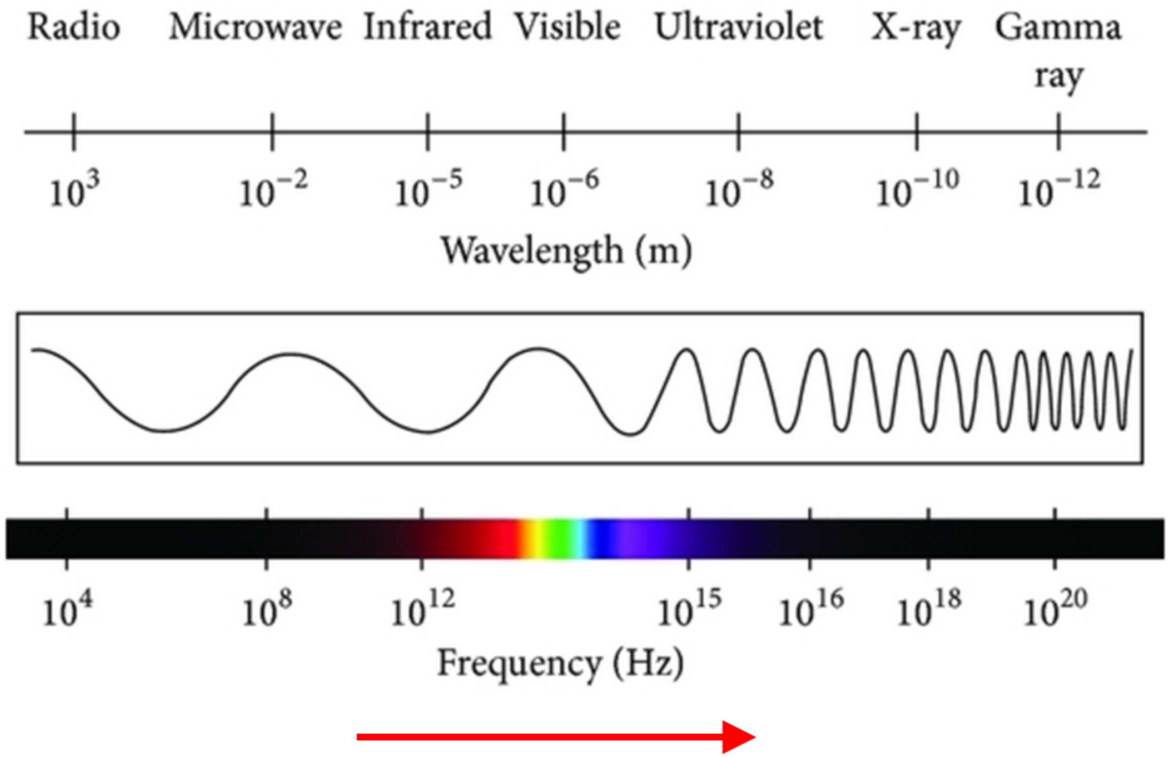

12
11.5
GHz
11
10.5
10
9.5
9
8.5
8
ℑ (k)
k


Temperature [°C]
6.46 × 10²
6.21 × 10²
5.95 × 10²
5.69 × 10²
5.43 × 10²
5.25 × 10²
5.07 × 10²



At 3 GHz, Wavelength 10 cm, “atom < 1 cm”





Infrared, Wavelength 700 nm, "atom < 70 nm"

(sub-100 nm "atom" sub-20 nm "feature size")

Conventional Techniques struggle with this size constraint, to produce meta-atoms in their millions with sub-20 nm "feature size".

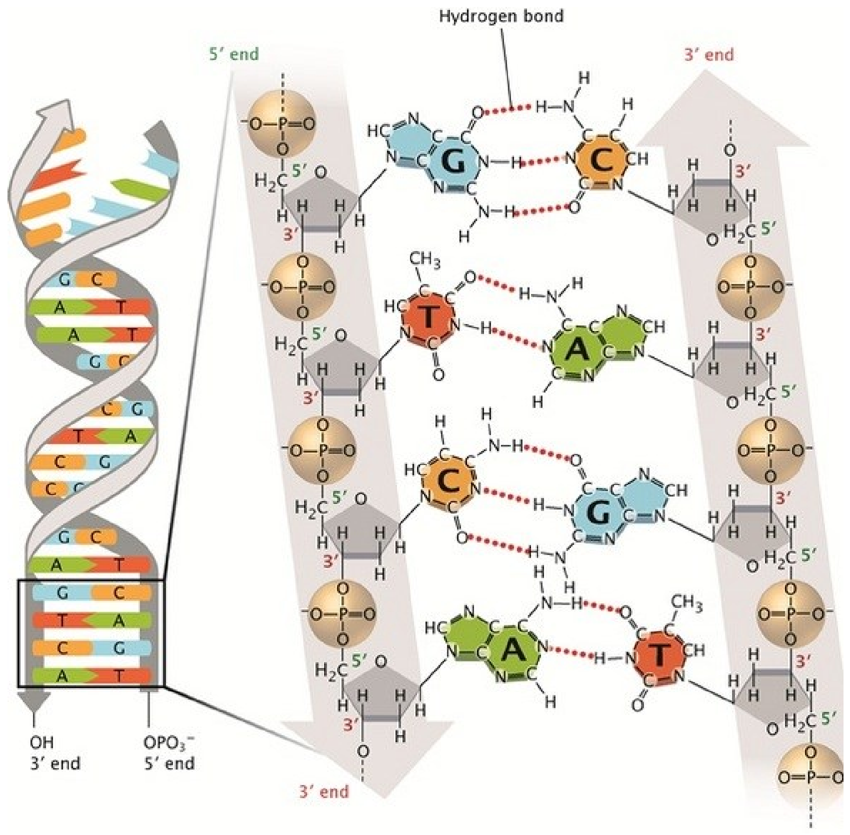
Conventional nanofabrication techniques

Technique	Resolution	Cost	Limitations	Throughput
Optical lithography	15nm	$30 million	2D, Photosensitive material	High
Laser interference lithography	20nm	$50,000	2D, Photosensitive material, Limits in design	High
Electron beam/Focused Ion Beam lithography	4nm	$2000000	2D, Photosensitive material	Low
Scanning Tunnelling Microscopy	Atomic	$30,000 to $50,000	Conductive material, V low throughput/construction in parallel not possible due to topological differences on the atomic scale	V. Low
Atomic Force Microscopy	Atomic	$30,000 to $50,000	V low throughput/construction in parallel not possible due to topological differences on the atomic scale	V. Low
Molecular Beam Epitaxy	45nm	£150,000	Crystalline structures greatly limit design flexibility, low resolution	High
Liquid Phase Epitaxy	50nm	£150,000	Crystalline structures greatly limit design flexibility, low resolution	High

Conventional nanofabrication techniques

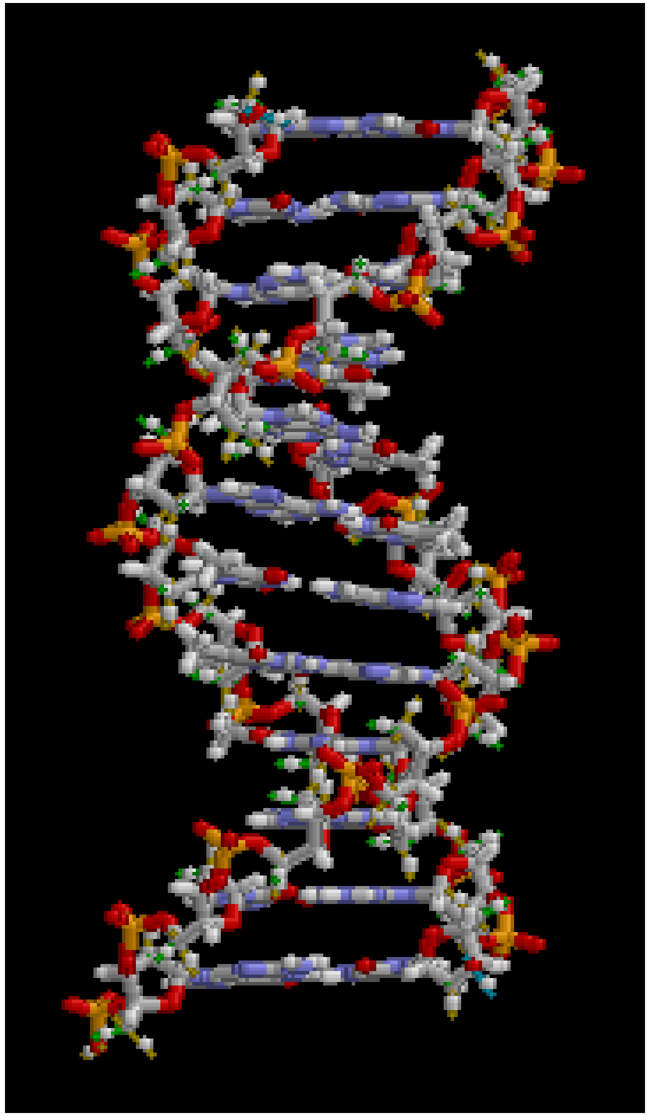
Technique	Resolution	Cost	Limitations	Throughput
Optical lithography	15nm	$30 million	2D, Photosensitive material	High
Laser interference lithography	20nm	$50,000	2D, Photosensitive material, Limits in design	High
Electron beam/Focused Ion Beam lithography	4nm	$2000000	2D, Photosensitive material	Low
Scanning Tunnelling Microscopy	Atomic	$30,000 to $50,000	Conductive material, V low throughput/construction in parallel not possible due to topological differences on the atomic scale	V. Low
Atomic Force Microscopy	Atomic	$30,000 to $50,000	V low throughput/construction in parallel not possible due to topological differences on the atomic scale	V. Low
Molecular Beam Epitaxy	45nm	£150,000	Crystalline structures greatly limit design flexibility, low resolution	High
Liquid Phase Epitaxy	50nm	£150,000	Crystalline structures greatly limit design flexibility, low resolution	High

Other technologies exist for resolution > 50nm i.e. roll-to-roll, etc

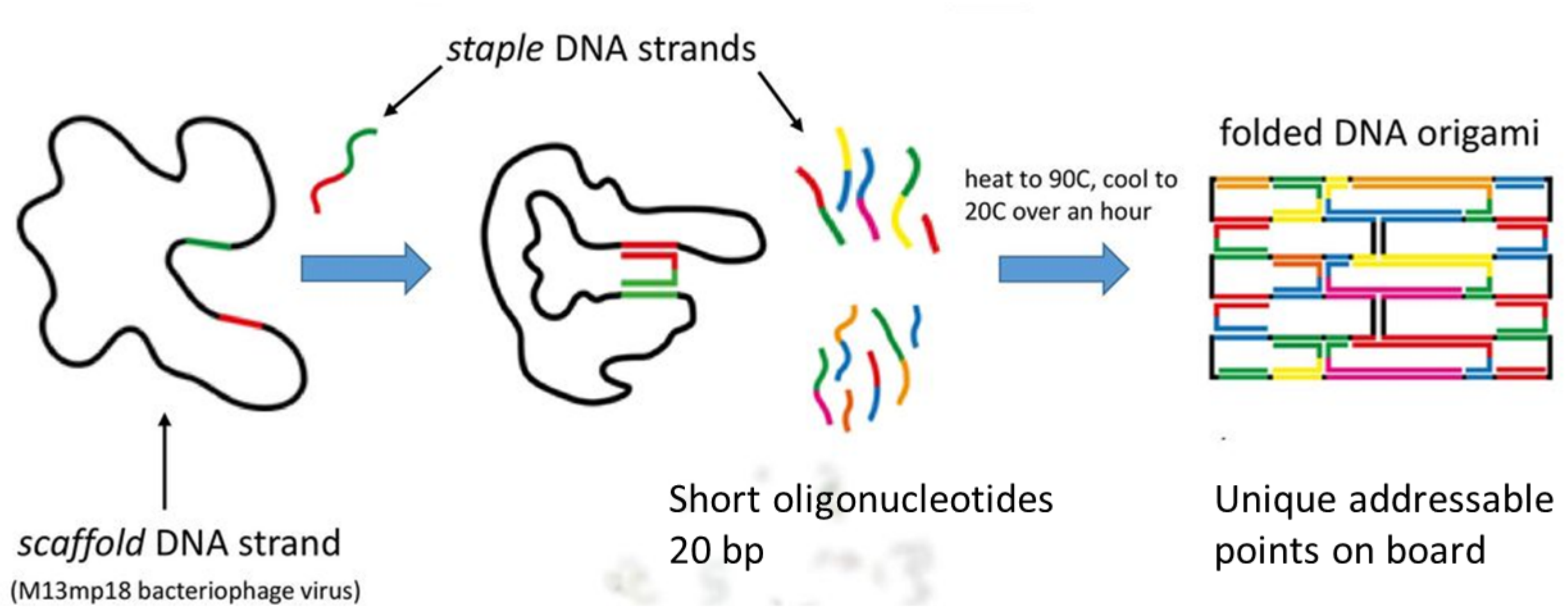


The Double Life of DNA

- In nature DNA carries information
- Encoded in the sequence of four nucleotides, or bases: ACGT
- Specific base pairing



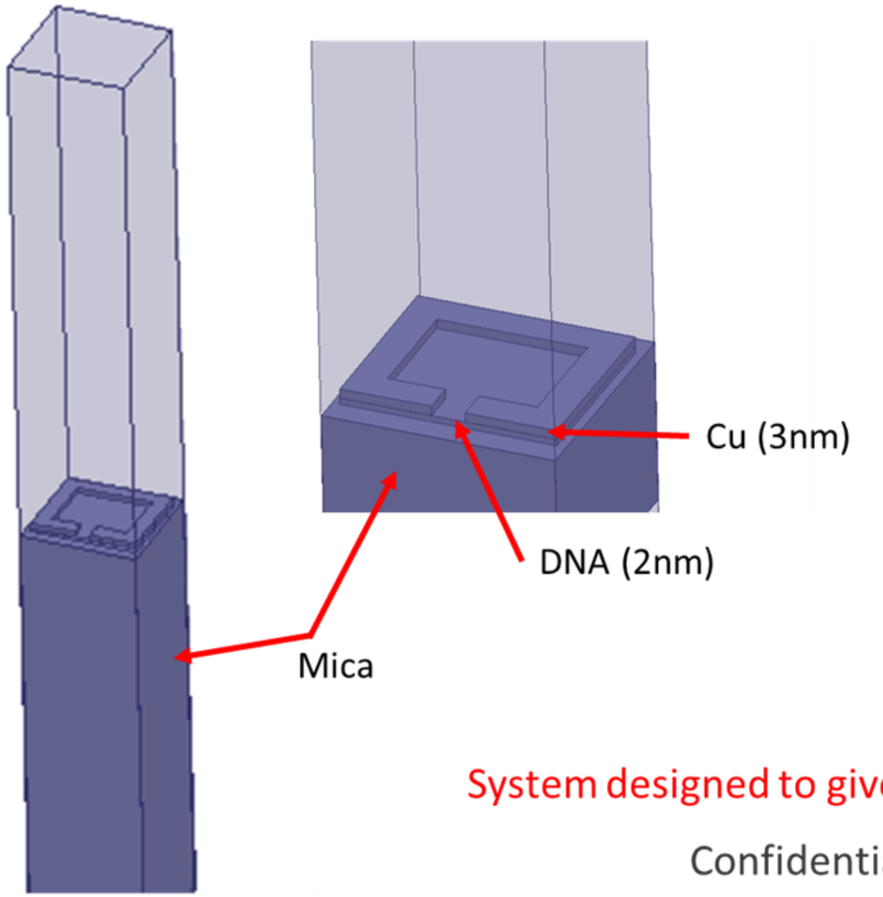
- Unique synthetic biology approach to scalable manufacturing of these metamaterials

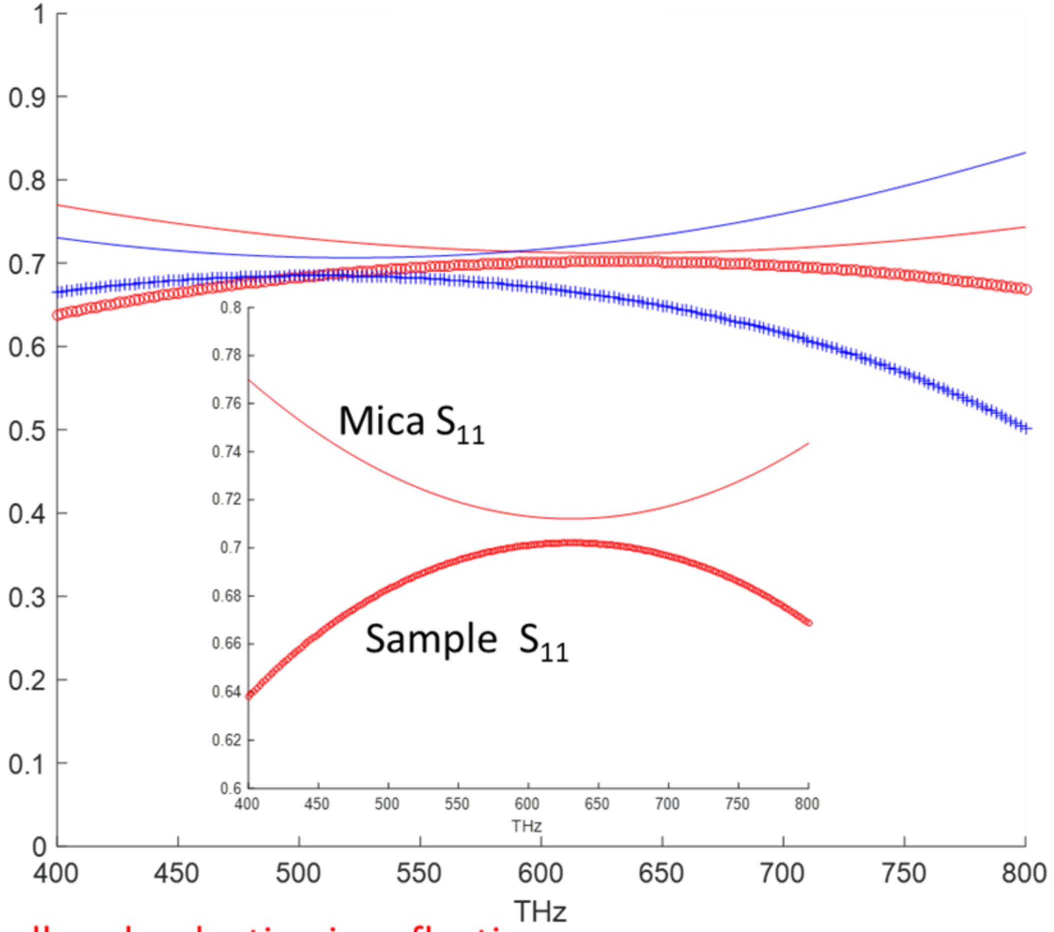


>7,000 base pairs (bp)
No repeated 10 bp series

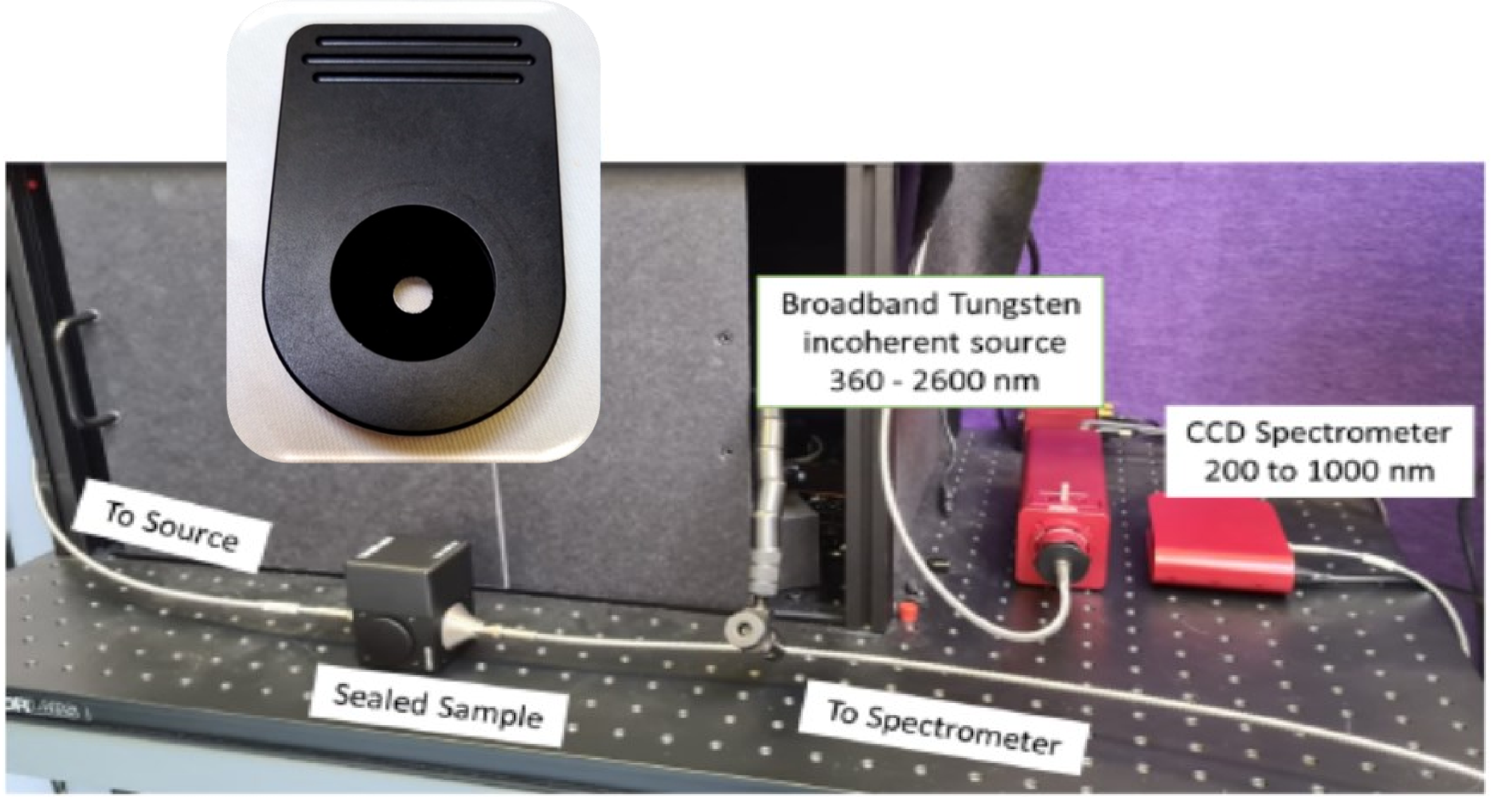
Commercial EM solvers are used to design meta-atoms to specific user requirements.

- Periodic BC model infinite sheet
- Incident plane waves





System designed to give broadband reduction in reflection


Broadband Tungsten
incoherent source
360 - 2600 nm
CCD Spectrometer
200 to 1000 nm
To Source
Sealed Sample
To Spectrometer

Summary

Can control Reflection/Transmission/Absorption and Particle Wave Interactions by design;

- Can design properties before fabrication
- Good agreement between design and manufactured properties
- Broad band response
- High-throughput High-fidelity Manufacture
- Mediate particle wave interactions via novel engineered dispersion relations

[dstl]
The Science Inside

Defence and Security Accelerator

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
UNITED STATES AIR FORCE

EUROPEAN OFFICE AEROSPACE R&D

BBSRC
bioscience for the future

EPSRC
Pioneering research and skills