

# Terahertz Radiation, Invisibility and Metamaterials

Dr. Alexander Argyros

Senior Research Fellow | Institute of Photonics and Optical Science  
School of Physics | The University of Sydney



THE UNIVERSITY OF  
SYDNEY

**IPOS**

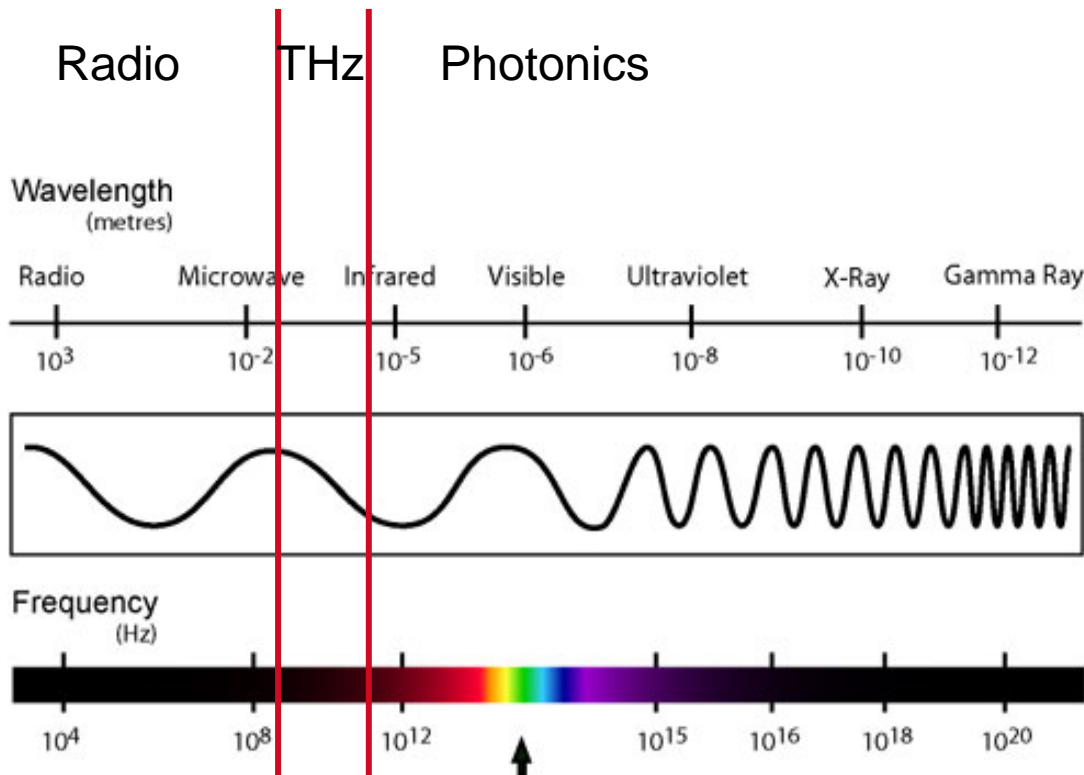
Institute of Photonics and Optical Science

- › Studied Maths and Physics here at Sydney Uni (including TSP Physics)
- › Honours in Physics here
- › PhD in Physics at the Optical Fibre Technology Centre
  
- › Postdoc Fellowship 2007-2009
- › In 2008 OFTC closed down, transferred to School of Physics as Senior Research Fellow
- › Australian Research Fellowship 2010 – 2014
- › Deputy Director of IPOS

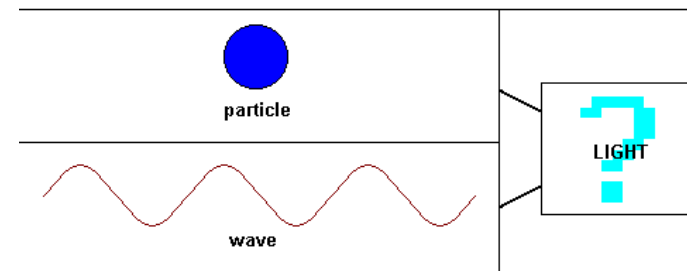
- › THz frequency radiation in the middle
  - Too microwave for photonics
  - Too photonics for microwave

0.1 – 10 THz

0.03 – 3 mm wavelength



Radio → Radio **Waves**  
 Photonics → **Photons**  
 THz → ?

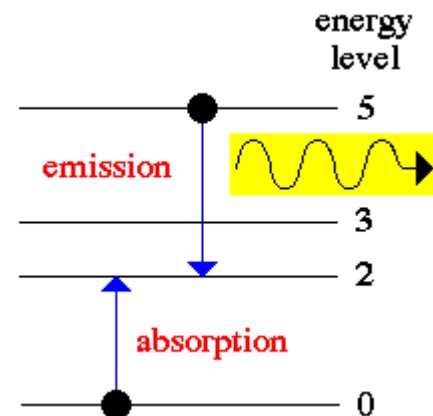
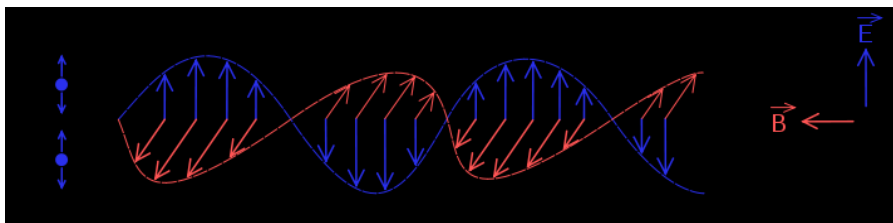
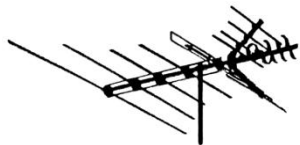
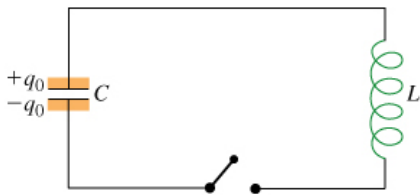


How to imagine the wave-particle duality.

- › Different technology used to play with radio waves and visible light
- › Electrons can keep up with a radio field but not light

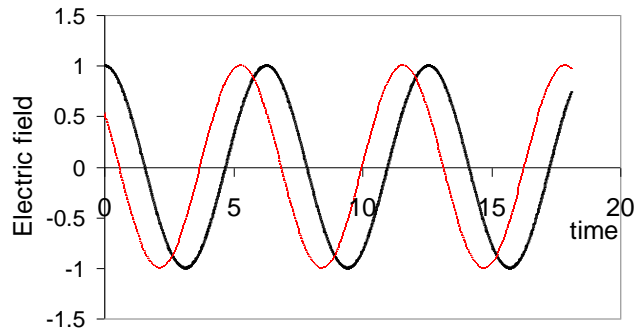
Circuits, current, antennae,  
**electric fields**

Atomic transitions, CCD arrays,  
intensity, film, **photons**

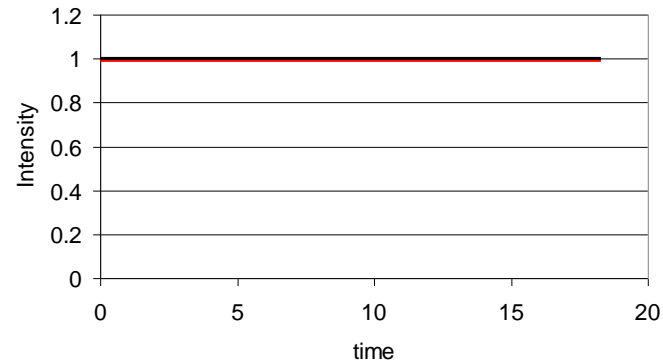


- › THz is enough like radio to be useful
  - ...detect electric field (wave), lots of materials transparent to it
- › THz is enough like light to be useful
  - ...high (enough) resolution images

$$E(x,t) = E_0 \cos(2\pi x/\lambda - \omega t + \varphi)$$

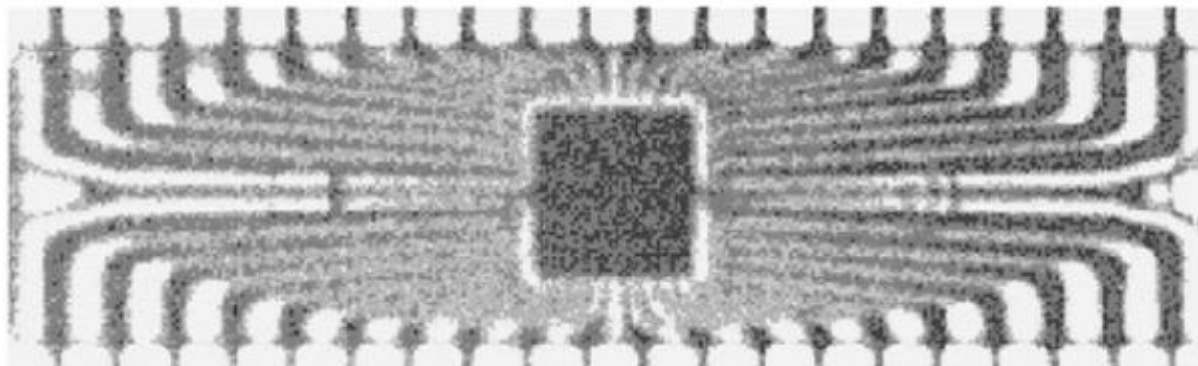


$$\text{Intensity} = E_0^2$$

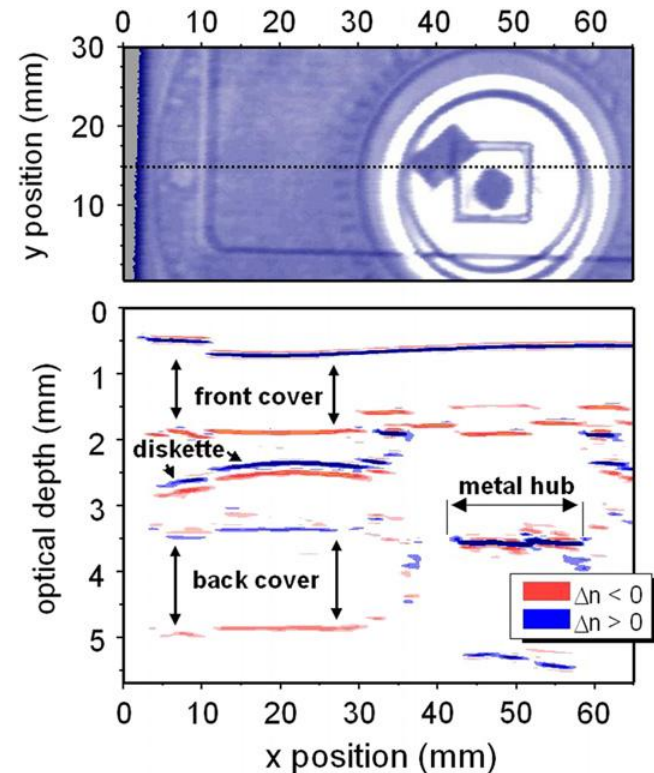
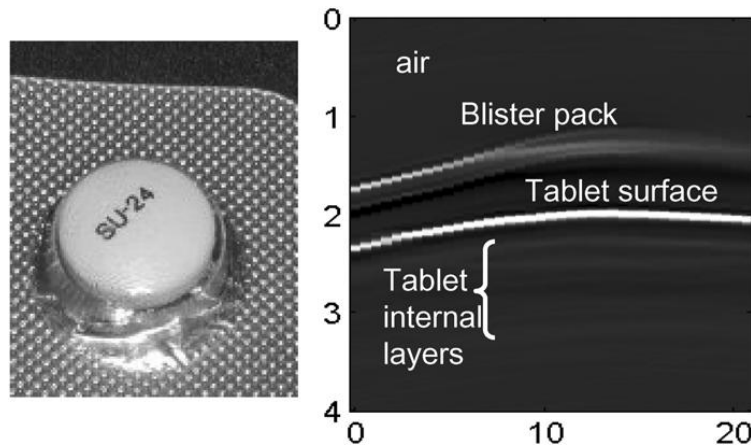


- › THz is enough like radio to be useful
  - ...detect electric field (wave), **lots of materials transparent to it**
- › THz is enough like light to be useful
  - ...**high (enough) resolution images**

Visible image



- › THz is enough like radio to be useful
  - ...detect electric field (wave), lots of materials transparent to it
- › THz is enough like light to be useful
  - ...high (enough) resolution images



- › Water is not transparent to THz radiation...

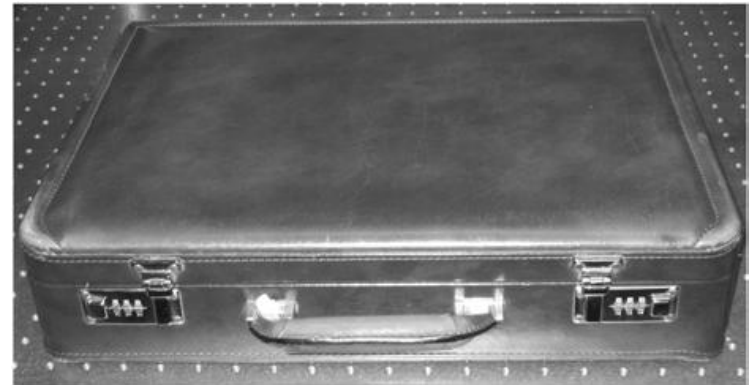


- › Plastic is generally transparent...





› And so are clothes and leather...



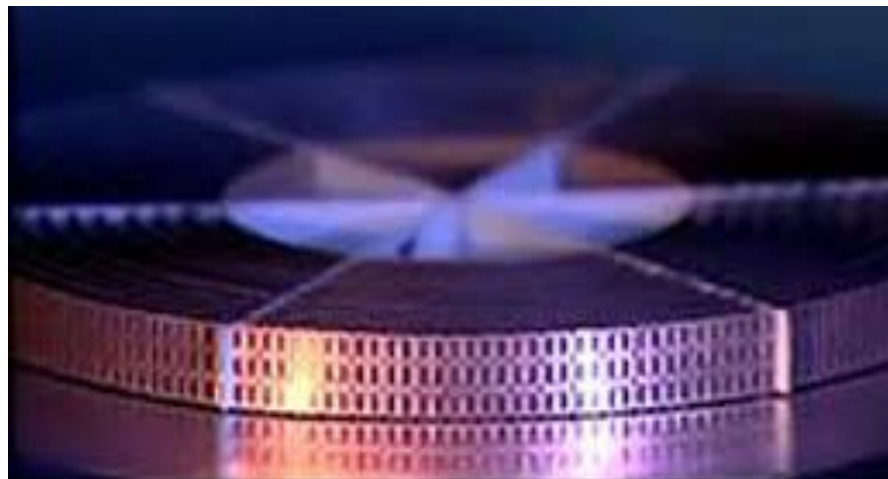
Sub-wavelength composites

Metal/dielectric – properties not achievable ordinarily, giving extraordinary (*tailored*) optical functionalities

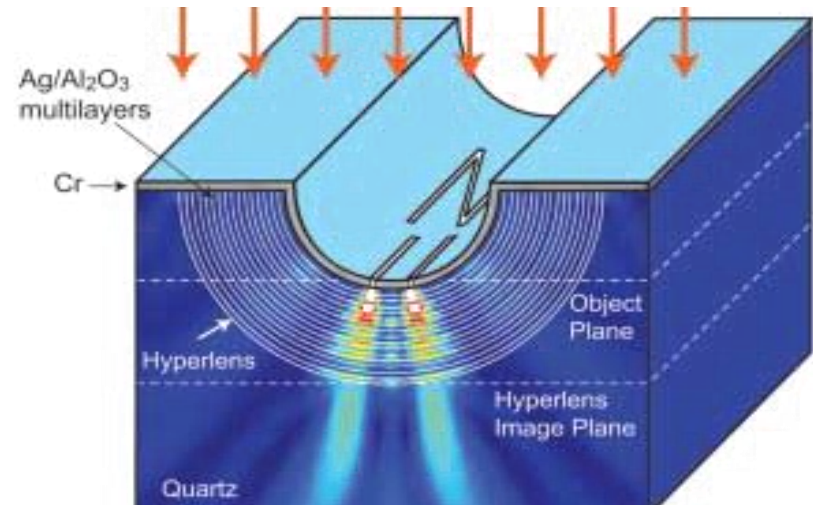
Negative refractive index, cloaking, invisibility, superlensing, etc...



O. Hess *Nature* **455**, 299 (2008)



D. Schurig et al., *Science*, **314**, 977 (2006)



Z. Liu, *Science*, **315**, 1686 (2007)

Refraction depends on refractive index  $n$

$$n = \sqrt{\epsilon\mu}$$

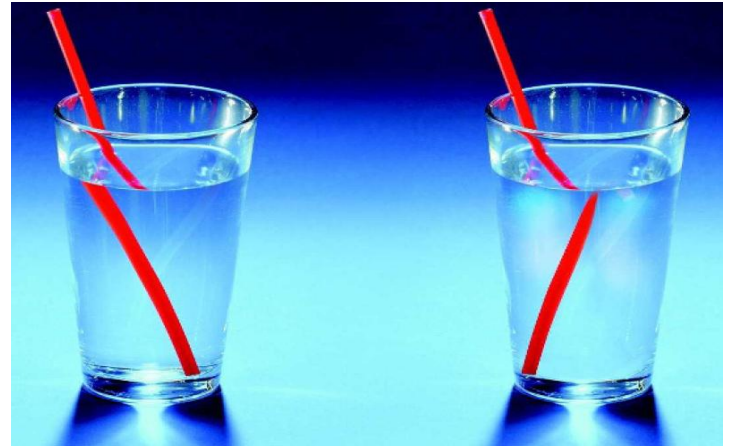
Refractive index depends on

Electric Permittivity  $\epsilon$

Magnetic Permeability  $\mu$

In all “normal” materials,  $n > 1$

In metamaterials you can control permittivity and permeability in such a way as to make negative refractive index



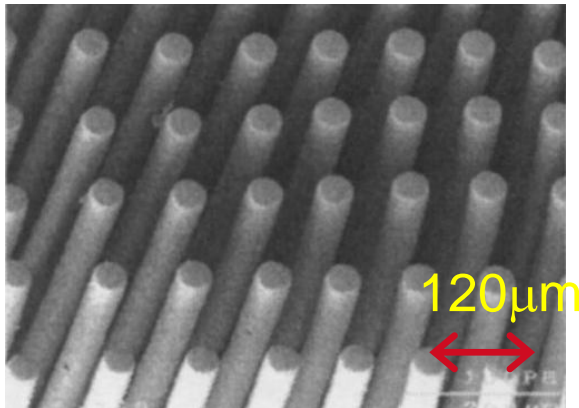
Snell's Law of Refraction

$$n_1 \sin \theta_1 = n_2 \sin \theta_2$$

Reflection coefficient at normal incidence

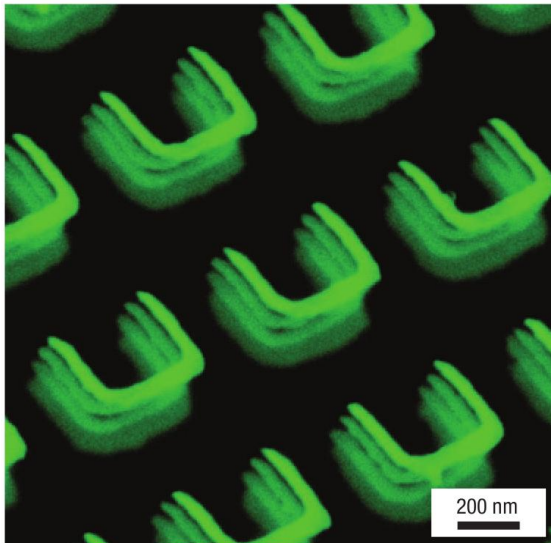
$$R = \left( \frac{n_1 - n_2}{n_1 + n_2} \right)^2$$

# Challenge: fabrication



**Typical feature size:**  
THz:  $< 100\mu\text{m}$   
Optical:  $< 200\text{nm}$

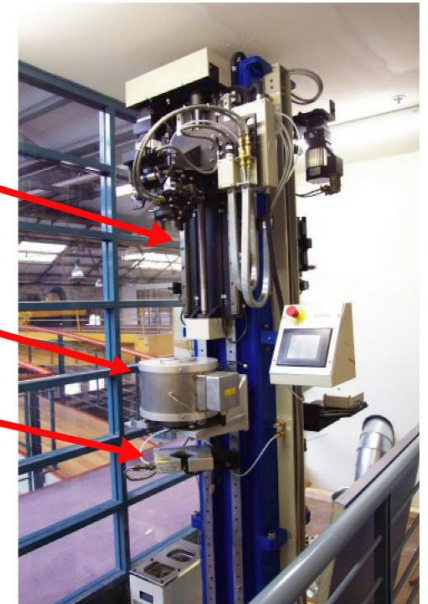
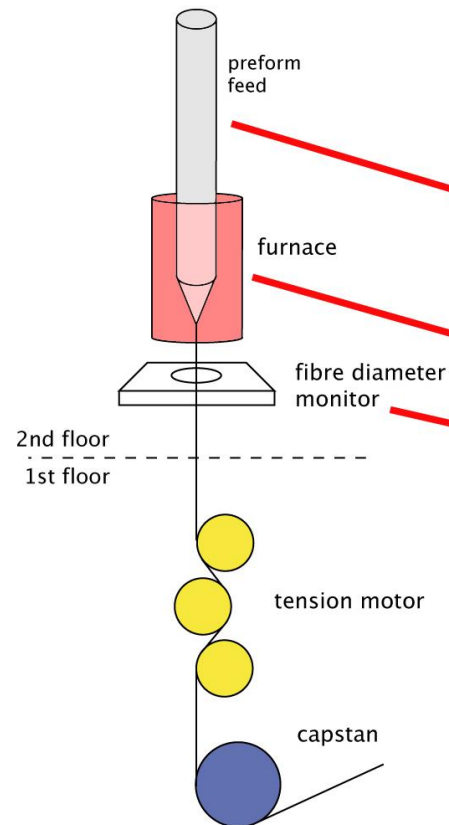
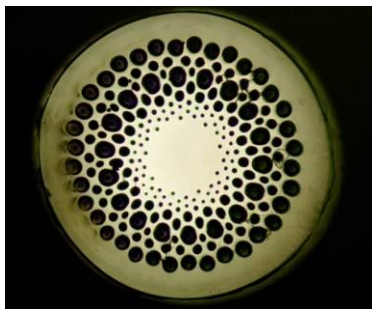
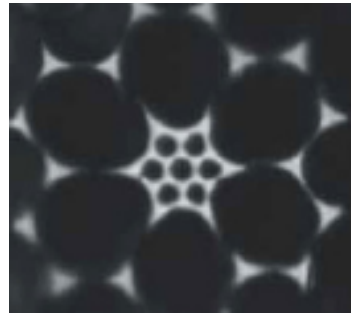
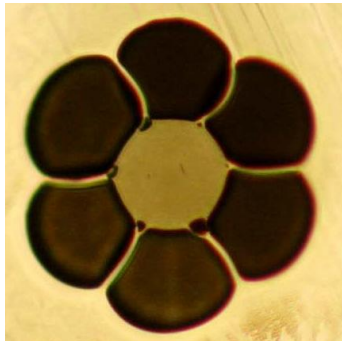
Expensive  
Small scale

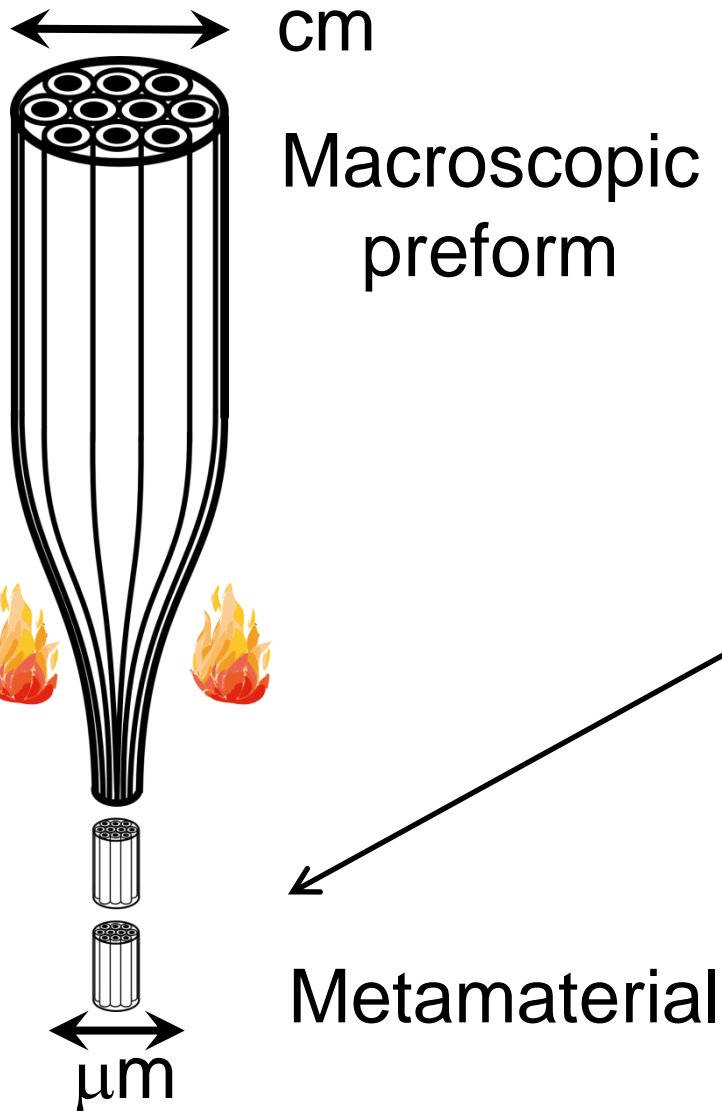


Our method:  
**Fiber drawing techniques**

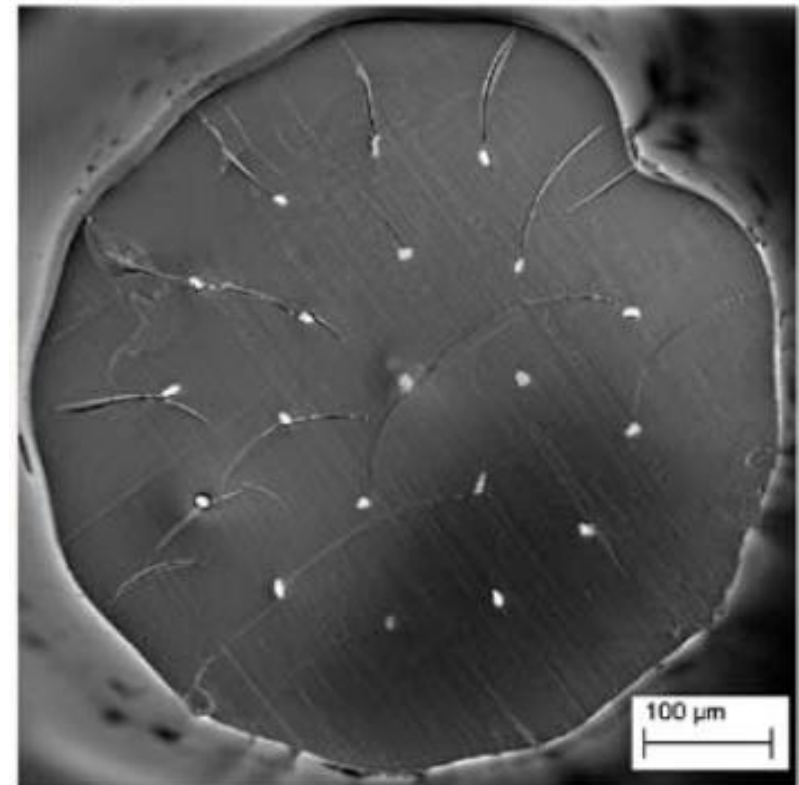
- > Microstructured optical fibres: structure on the micron scale.

Microstructure + Metal = Metamaterials





PMMA & indium

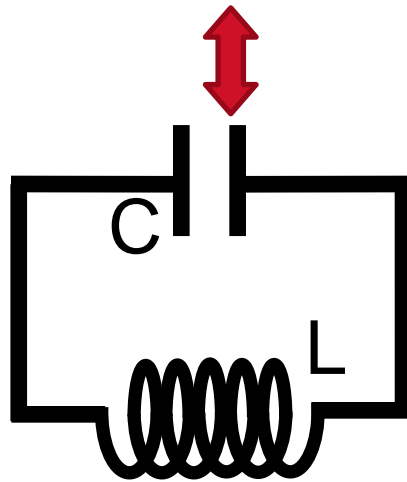
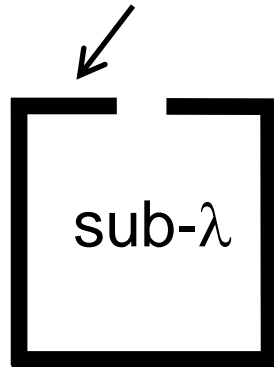


Tailored (negative) electric permittivity

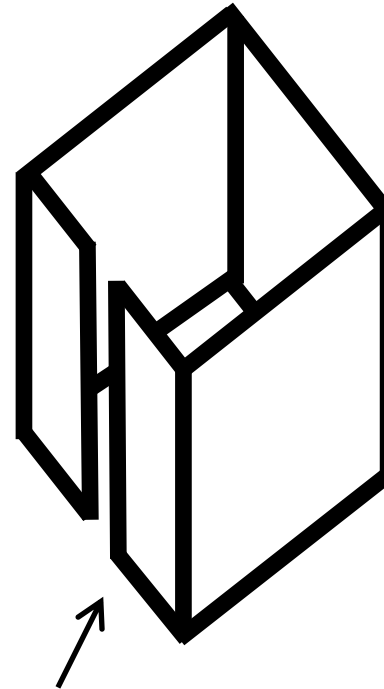
A. Tuniz et al. APL **96**, 191101 (2010)

# Tailoring the (THz) magnetic response

Metal split-ring resonator (SRR)

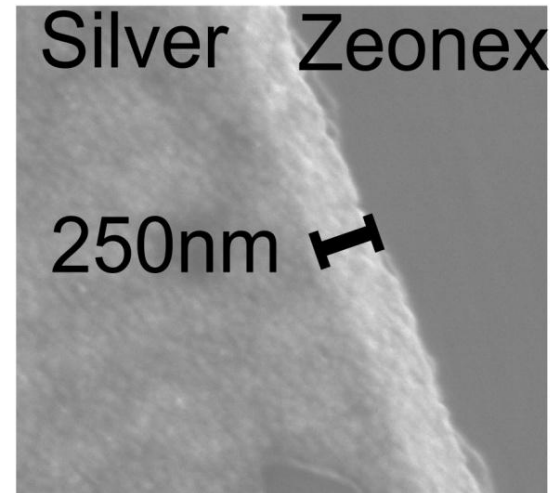
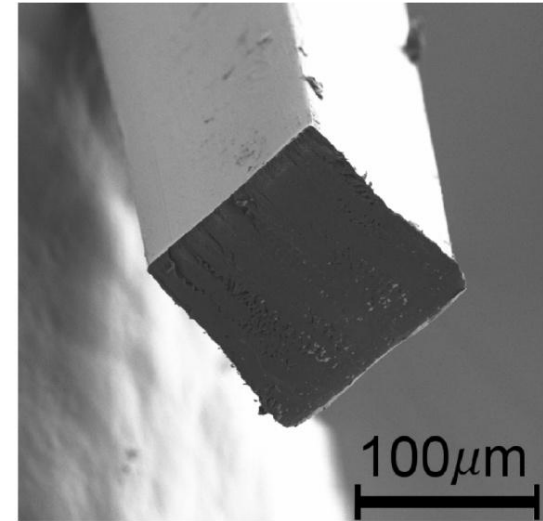
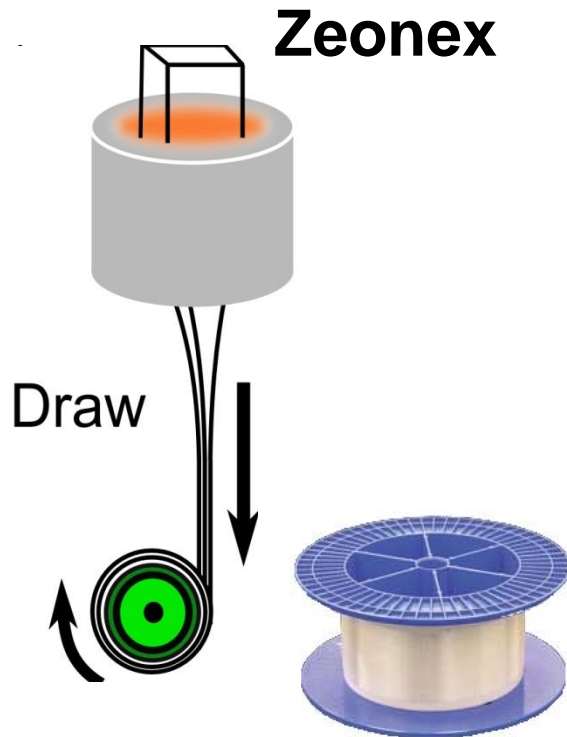


$$\omega_R = 1/\sqrt{LC}$$

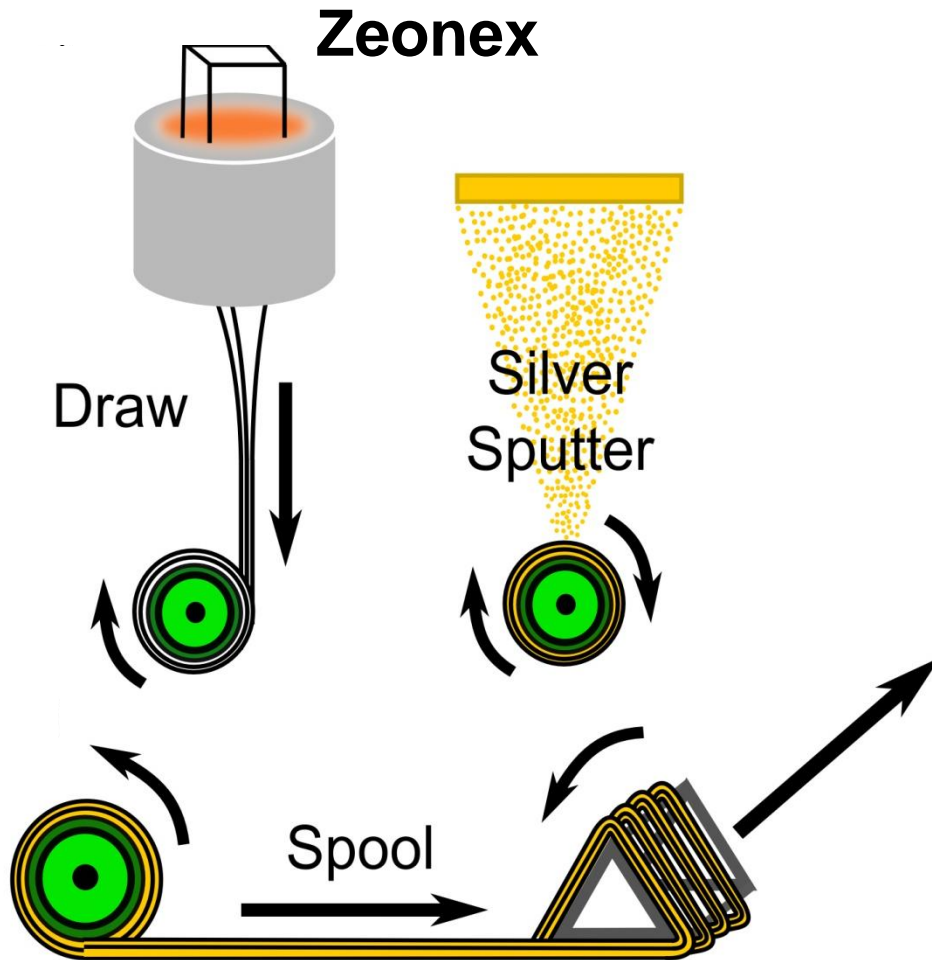


In-fiber: 2-dimensional slotted resonator  
(invariant along longitudinal axis)

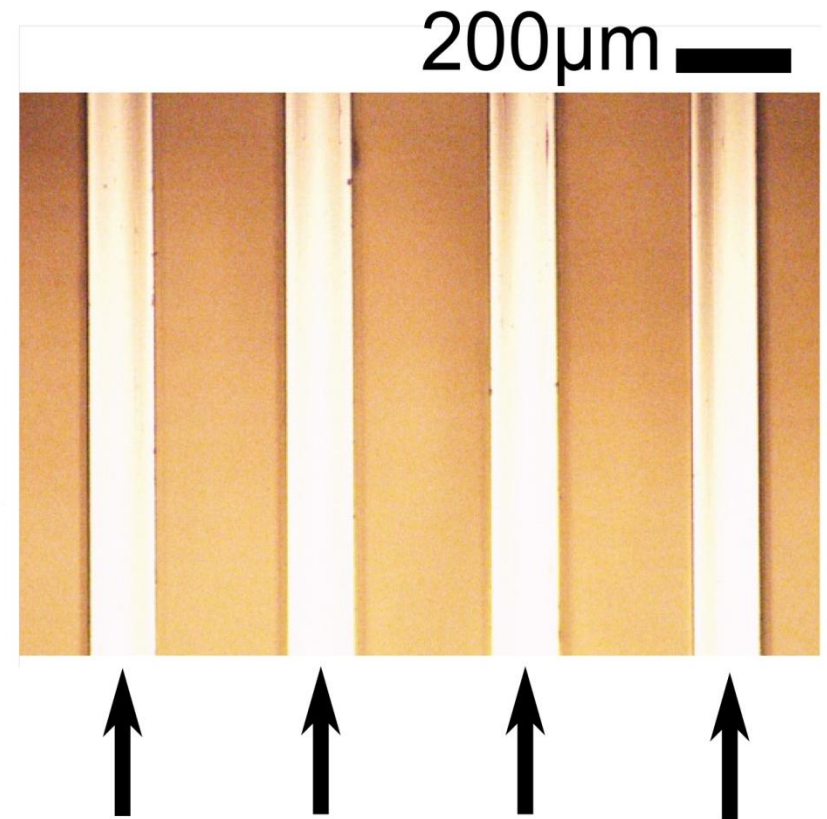
# How do we do this in fiber?



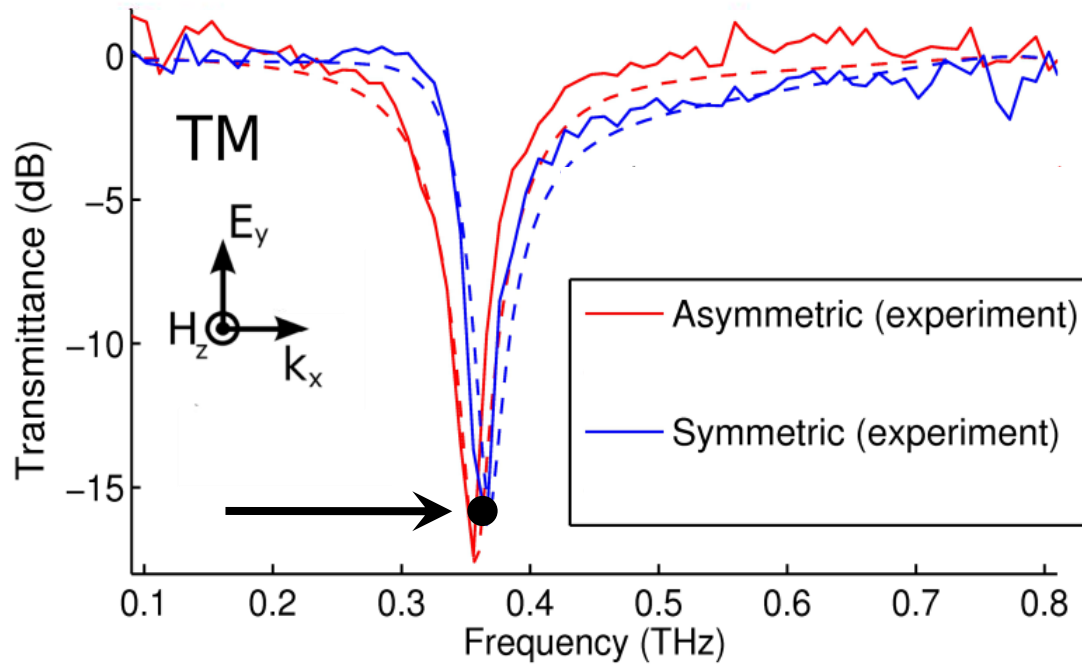
# How do we do this in fiber?



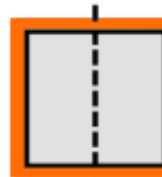
## Metamaterial fiber array



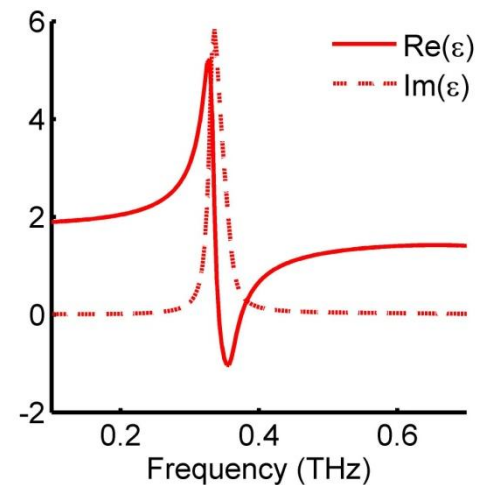
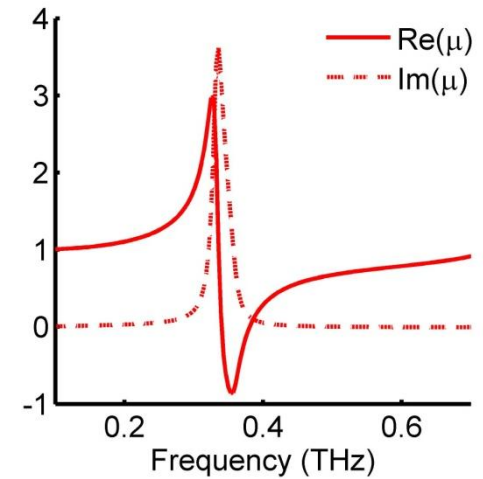
# Experimental and numerical results (TM)

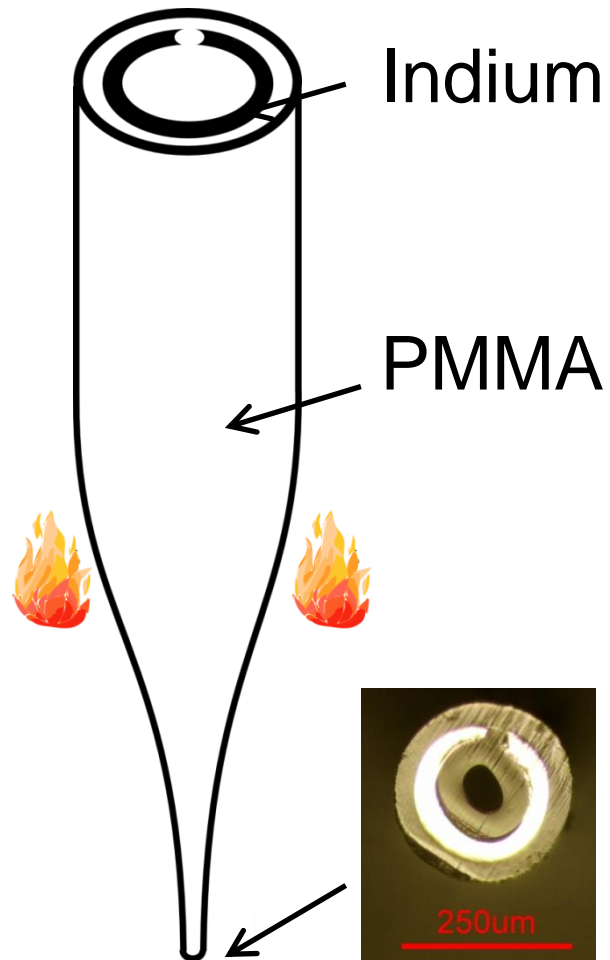


Symmetric

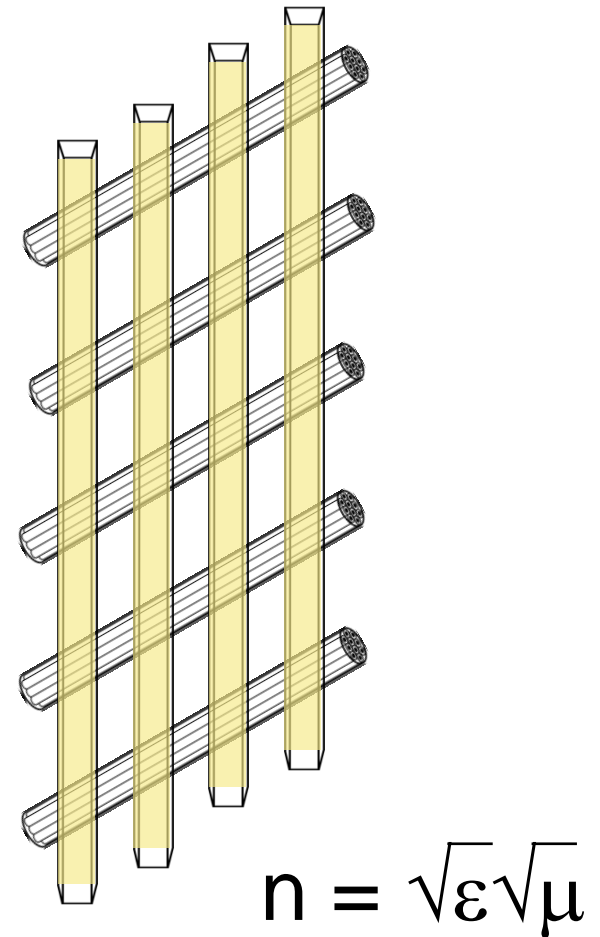


Asymmetric



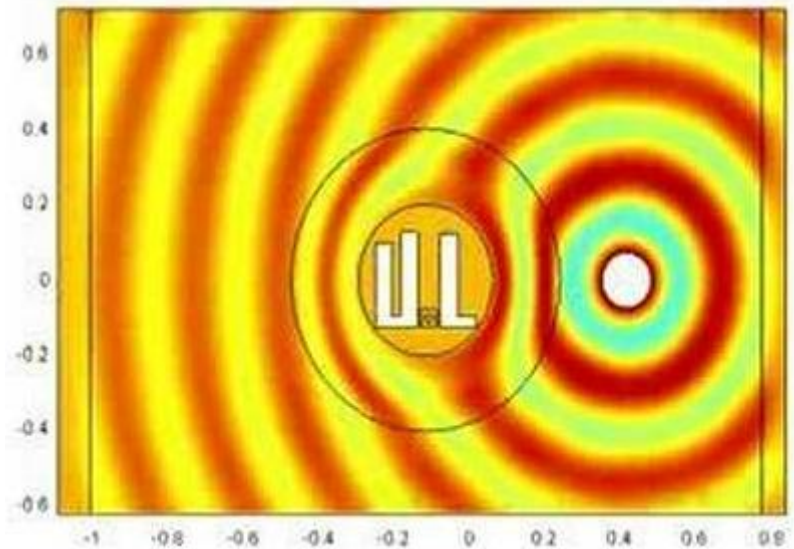
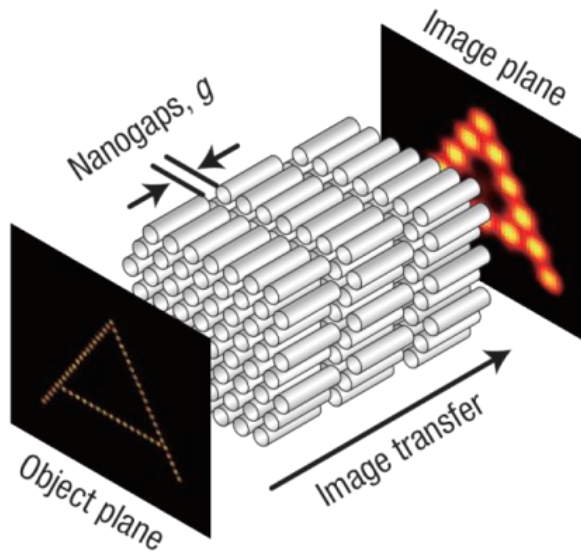
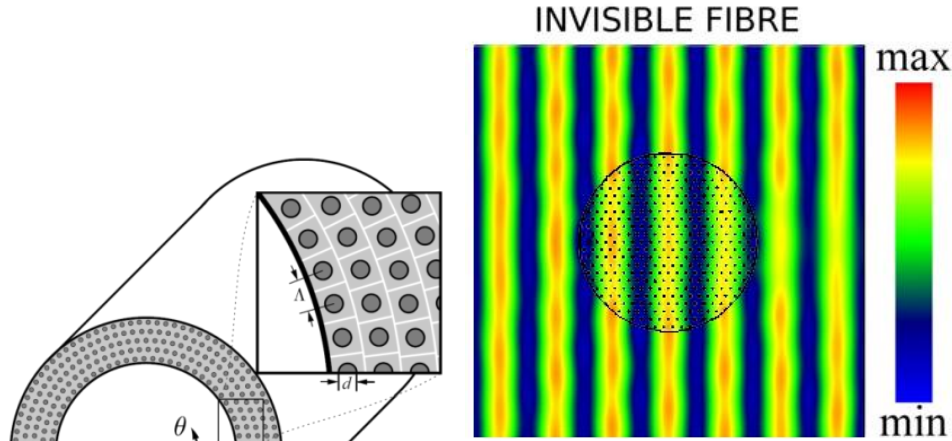


Direct-drawn resonators



Woven structures

# What if we could go smaller?



- › THz radiation is a relatively new field being explored
- › Opportunities for imaging and sensing
- › Opportunities for exploring new physics and application through metamaterials
- › Lots of work being done here in the School.