Plasmonic Antennas & Metamaterials on Quantum Cascade Lasers

David Austin[1]
Supervisor: Luke Wilson[1]
Collaborators: Ali Adawi[1], Dmitry Revin[1], Mike Soulby[1], John Cockburn[1]
Isaac Luxmoore[2], Qi Jiang[2], Andrey Krysa[2], Paul Fry[2]
Paul-Arthur Lemoine[3], Yannick De Wilde[3]

[1]Department of Physics and Astronomy, University of Sheffield, UK
[2]Department of Electronic and Electrical Engineering, University of Sheffield, UK
[3]Laboratoire d'Optique Physique, Ecole Supérieure de Physique et de Chimie Industrielles, Paris, France

Aim

- To produce an enhanced near field at the facet of a Quantum Cascade Laser, for use in future vibrational spectroscopy studies. This is achieved by patterning the gold-coated facet with a focussed ion beam (FIB).

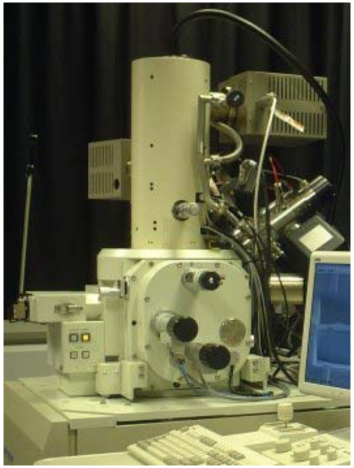
Outline

- Antenna design
  - Bowtie, inverse bowtie and X shaped antennas simulated using the FDTD method
  - The FIB parameters, and resultant structures obtained

- Mid – IR SNOM measurements
  - The a-snom technique. a-snom as applied to facet patterned QCLs, with preliminary measurements of the near field of the various structures
  - FDTD simulations of the antenna-SNOM tip interaction

- Split ring resonator arrays
  - A brief introduction to metamaterials, and their uses
  - Metamaterial / QCL hybrids, and their potential benefits
  - Metamaterial designs on QCL facets
  - Transmission experiments

Fabrication



JEOL 'Fabrika'

• The QCL facet is HR coated with 200nm MgF followed by 50nm Au, on the emission side

• A focussed ion beam system, the JEOL 'Fabrika', is then used to pattern the gold with a resolution down to 7nm

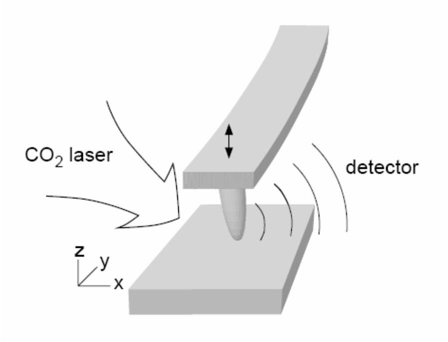
• The JEOL 'Fabrika' is based upon a JEOL 6500F SEM with an Orsay Physics Ga+ ion column attached

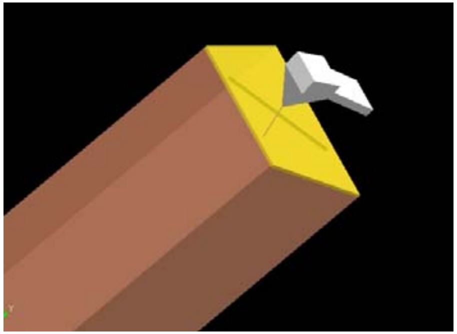
• Structures designed on 'Raith' software, and patterned onto the gold using a single pass, to improve uniformity

a-SNOM Measurements

- In scanning near field optical microscopy (SNOM), the light is forced through a small aperture (~ hundred nm), to provide a high resolution image
- The most common configuration uses a sharpened optical fibre
- This has a low transmission, with associated low signal strength since the sharpened fibre acts as a cutoff waveguide near the apex
- Wavelength limited, so cannot be used effectively at longer (mid-IR) wavelengths
- Apertureless SNOM provides ultrahigh resolution independent of the wavelength

- In a typical apertureless SNOM experiment, an external laser is focussed on the oscillating SNOM tip to provide illumination





- In our configuration, the QCL is used as the laser source, and the a-SNOM tip is scanned across the fib-milled facet

QCL with SNOM tip on antenna

Near Field Antenna Designs

FDTD Simulation of Bowtie Antenna

- Designed using fully 3D FDTD Simulations (XFDTD[1]), specifically for the wavelength of operation of the QCL

- Gold parameters determined by Drude model, with n,k = 8.06, 45.2 (Palik 1998)

- Finite difference time domain (FDTD) is an accurate and widely used technique based on the meshing of the structure into Yee cells, where the Maxwell EM equations are solved at each of the boundaries

- In the antenna simulations, the enhancement is normalized to the incoming sinusoidal plane wave (set at 1V)

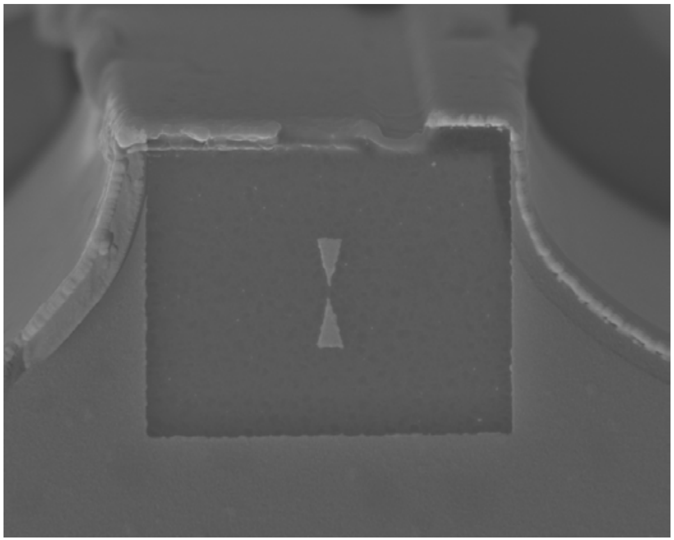
- The above image shows a maximum electric field enhancement factor of 60

- Note the small (tens of nanometres) area of enhancement

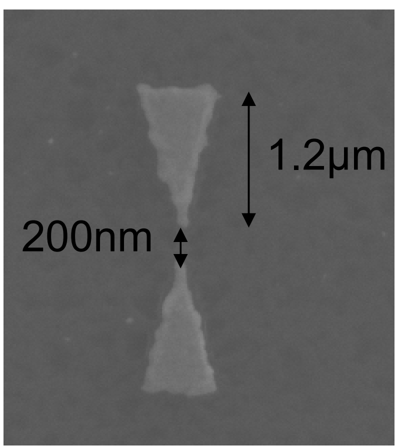
[1] – XFDTD is a commercial software package

Near Field Antenna Designs

FIB Patterned Bowtie Antenna

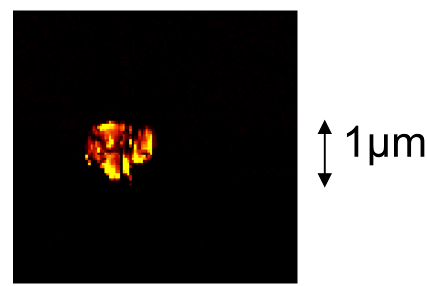


Close up of the antenna



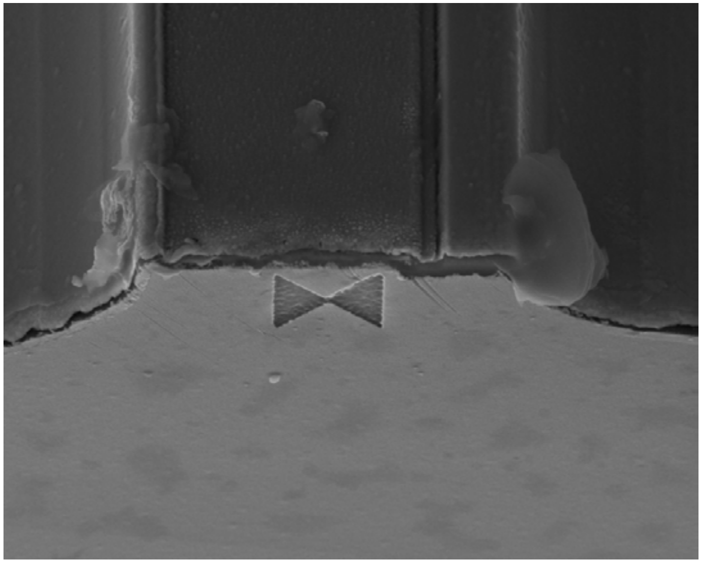
- Gap size determines coupled enhancement of the field (~wavelength independent)
- The enhanced near field is in a small (~ few tens nm) region at the centre
- Therefore the gap size is too large to observe strong coupled enhancement (ie. enhancement stronger than single antenna structures)
- But the SNOM tip size precludes that level of fine structure resolution in this case (radius of curvature ~70nm)
- Near-field image smeared out over the antenna, so difficult to interpret

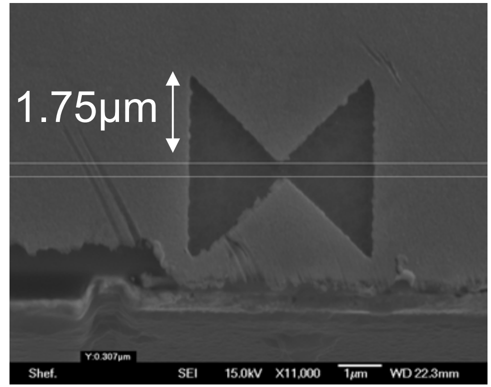
a-SNOM Measurement



Near Field Antenna Designs

Inverse bowtie design FIB patterned onto facet



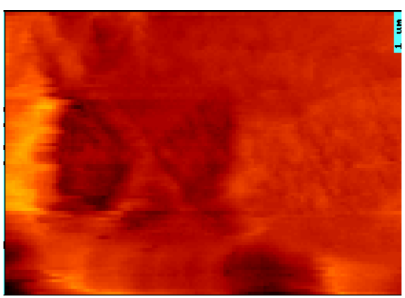


300nm gap

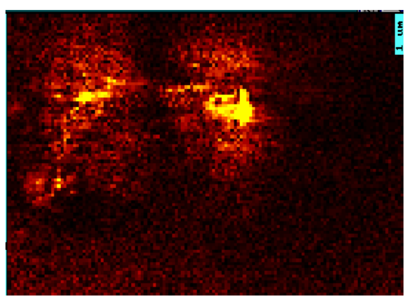
Close up of antenna

- Different antenna size to match operating wavelength of QCL
- a-SNOM results show an enhancement, but overwhelmed by scattering from the side regions

AFM

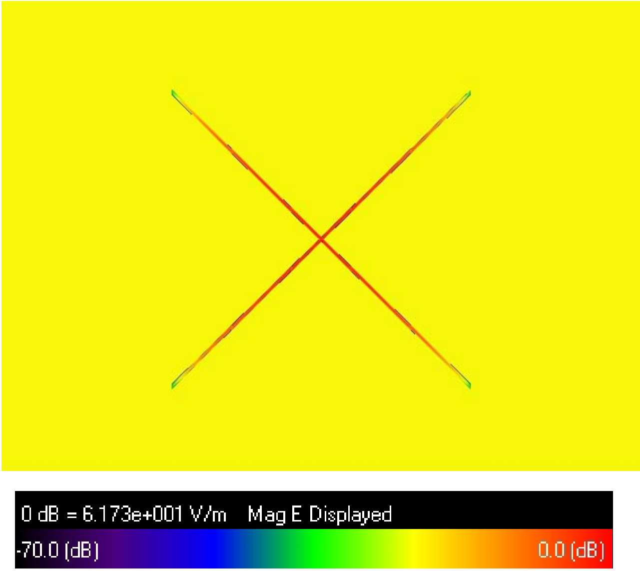


a-SNOM



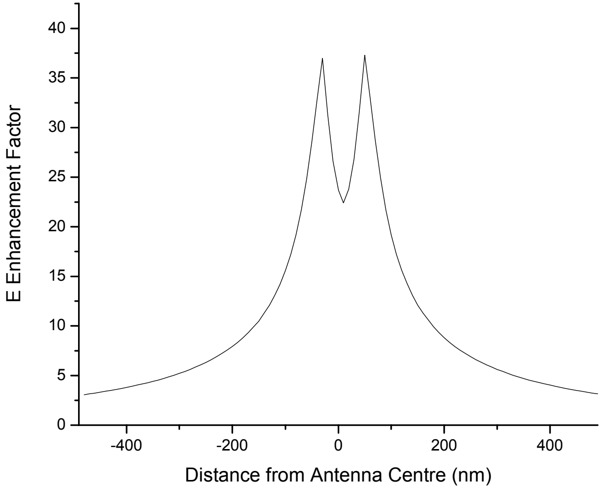
X - Antenna for Near Field Enhancement

- New X-shaped design reduces area etched off
- Emission from ‘open’ areas reduced, so plasmonic enhancement should be easier to measure
- Gold facet facilitates surface binding, so reducing the area etched off is advantageous for vibrational spectroscopy



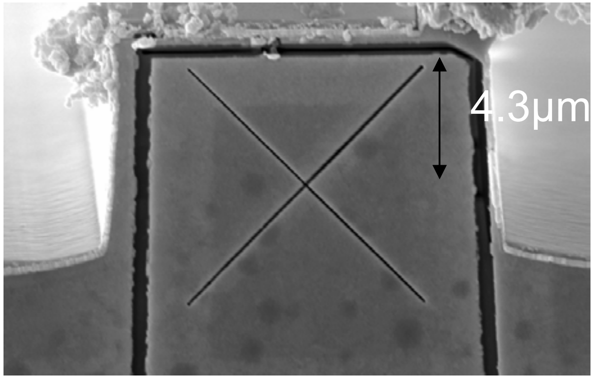
FDTD Simulation of Near Field of X-Antenna

Enhancement 10nm Above X-Antenna

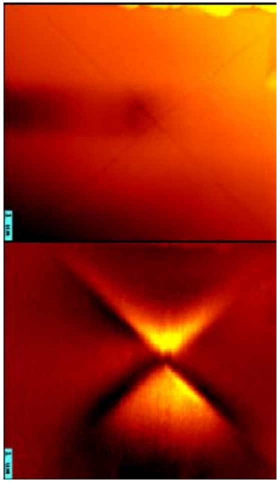


- Smaller gap size (50-100nm), so greater coupling and relatively stronger enhancement factors
- Expected max E-field enhancement at the centre of the antenna is 62×
- 30% dip in enhancement at the centre (for 100nm gap)

~12μm QCL (MR2400) With X-Antenna



100nm Gap



AFM

a-SNOM

$$L_{antenna} = \frac{\lambda}{2n}$$ (first order)

• As expected, the enhancement is in the TM direction, indicative of a plasmonic enhancement

• As with the inverse bowtie antennas, there is a disparity between simulation and experiment

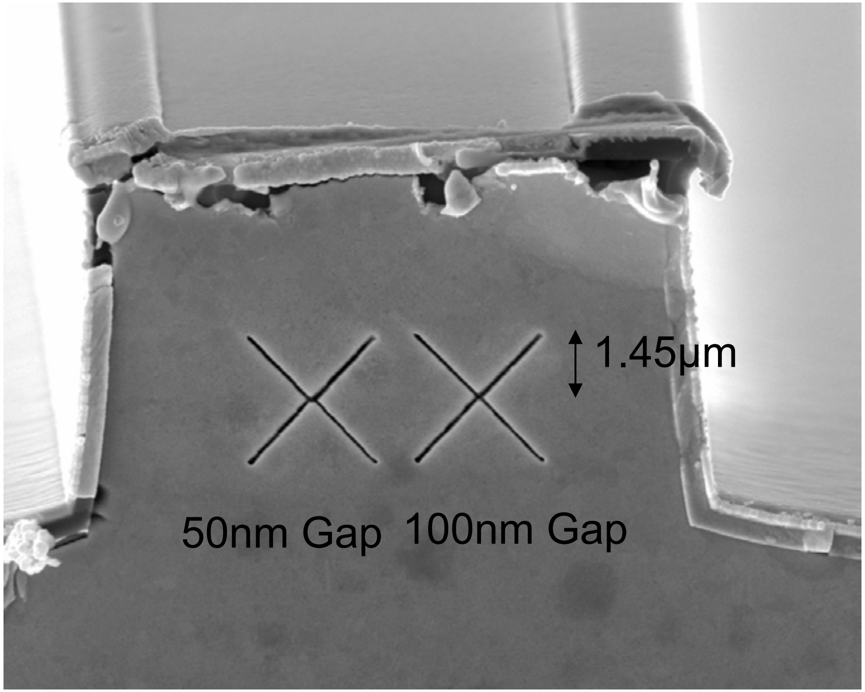
• Enhancement should be greatest at the centre

• Probably due to the large SNOM tip size

• To understand this, we carried out simulations of the tip-antenna interaction

• We also looked at the enhancement associated with different orders (corresponding to the length of the antenna)

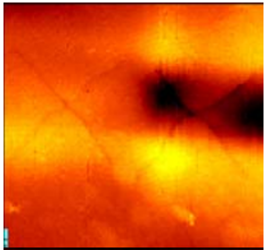
~12μm QCL (MR2400) With X-Antenna



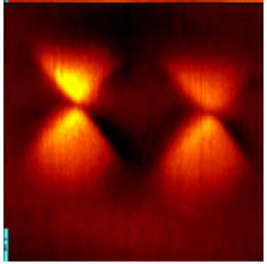
$$L_{antenna} = \frac{\lambda}{6n}$$ (higher order)

- Higher order antennas essential for long wavelength QCLs (to fit on facet)
- Simulations show similar values for the enhancement

AFM

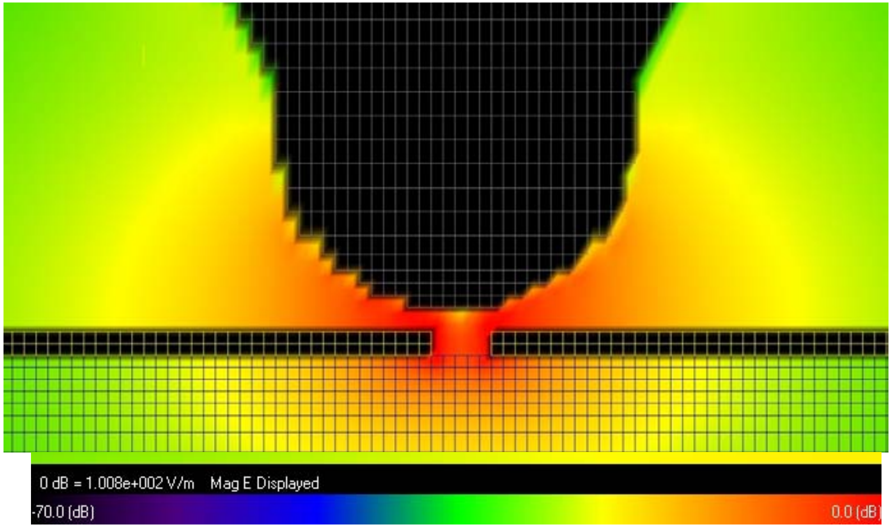


SNOM

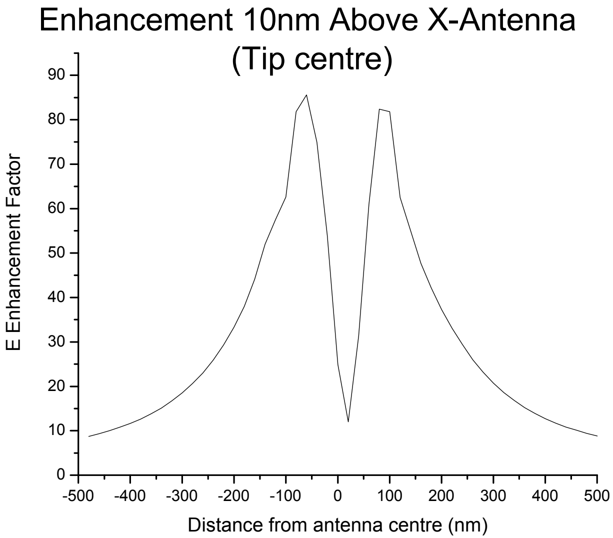


- a-SNOM results are similar to the large X-antenna
- Stronger enhancement expected in the 50nm gap antenna, due to the coupling of the enhancement

Antenna – SNOM Tip FDTD Simulations (side view)



• Bringing the Tungsten a-SNOM tip to within 40nm of the antenna effectively doubles the Electric field enhancement to 100.8×



• The enhancement becomes sharper, with a stronger relative decrease at the centre (~85%)

• This shows something similar to the experiments, with a strong decrease at the very centre of the antenna

• If the SNOM tip is scanned across the surface, the enhancement at the edges of the antenna become even more apparent

• Explains the enhancement above the metal, where the field should be zero

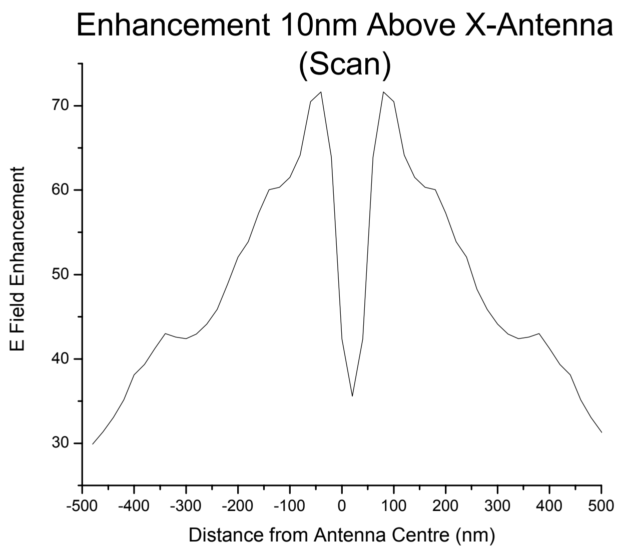
Antenna – SNOM Tip FDTD Simulations (side view)

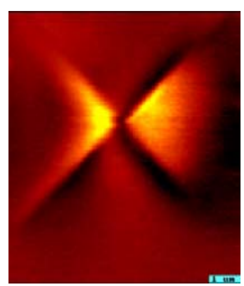
- With SNOM tip 100nm off-centre, the enhancement is further increased, and the profile is modified

- Even with the SNOM tip 500nm away from the centre, there is an associated enhancement

- a-SNOM is not a passive probe for plasmonic structures

- If we superpose the results as the tip scans across the antenna, the following occurs





- Due to the size of the SNOM tip, the enhancement in the centre is ‘shadowed’

Metamaterials

- A metamaterial is a material where the optical properties are determined artificially. For the incident radiation, the structure of the metamaterial is indiscernible, so the patterned metal acts as artificial atoms

- This was first proposed by Veselago in 1968, who considered the possibility of negative refraction. It was later investigated by Pendry, who then proposed possible structures to tune the electric permittivity and magnetic permeability to take negative values

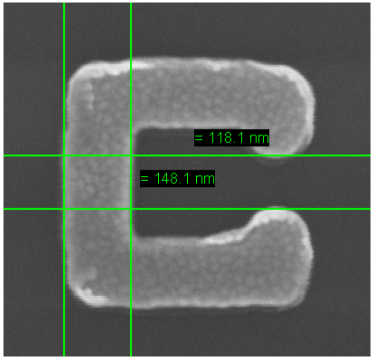
- Negative refraction[2], perfect lenses[3], cloaking technologies[4] etc. are some of the recent theoretical/experimental advancements in the field

- For the work here, we looked at split ring resonators (SRRs) which are often the building blocks of a negative permeability material, but here the emphasis is on their near and far field properties

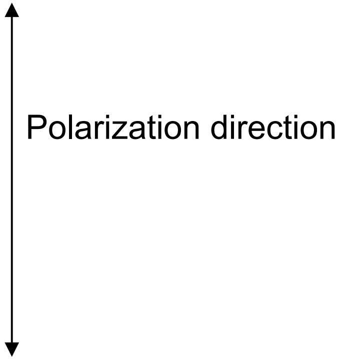
[2] – H.J. Lezec et al, Science, 316, pgs. 430-432 (2007)
[3] – J.B. Pendry, PRL, 85,18 (2000)
[4] – J.B. Pendry at al, Science, 312, 1780 (2006)

Metamaterials

- The split ring resonator was introduced by Pendry in 1999



An SRR on GaAs



- The shape acts like an LC circuit, with the loop acting as a single winding of an inductance coil, and the gap like that of a capacitor

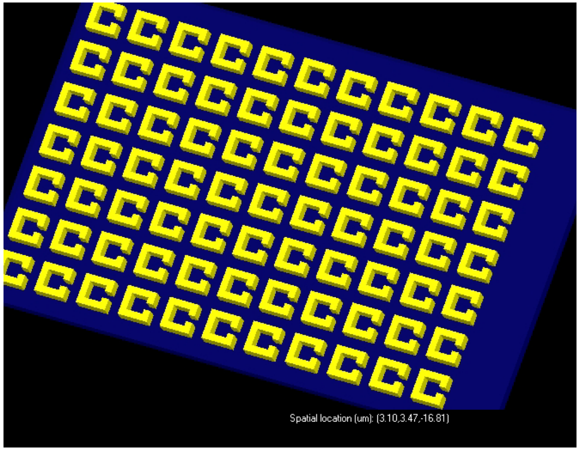
- Strong magnetic behaviour is associated with the strongly inhomogeneous fields around the structure

- Local field strengths orders of magnitude larger than in free space

Metamaterials

- The SRRs are a capacitor like element for the incident EM field, with an associated LC resonance frequency
- The interesting properties of SRRs are manifest at these frequencies

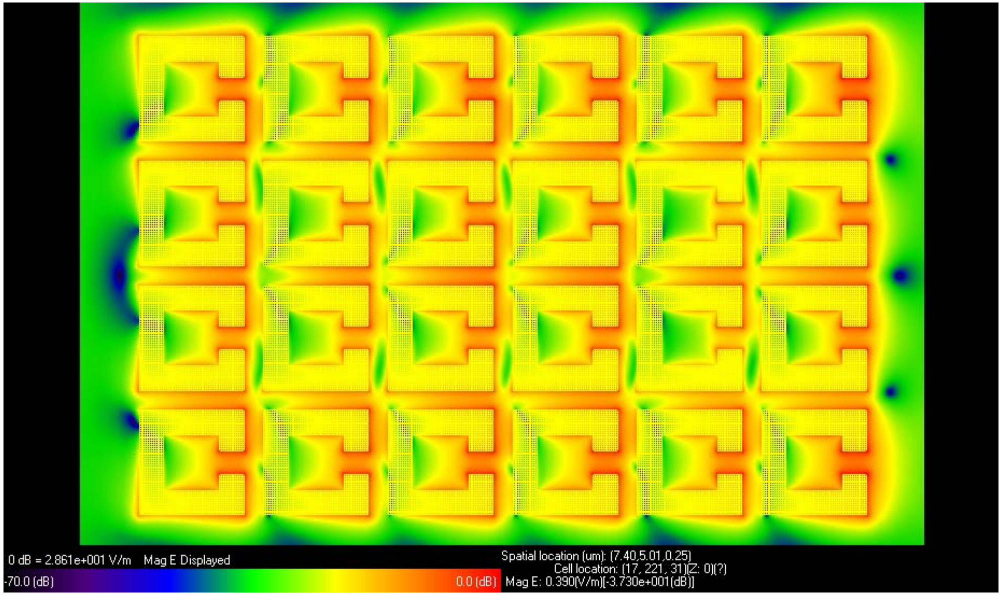
- By optimizing the geometry of the SRRs, this LC resonance can be chosen to occur at the QCL emission frequency



An SRR array in XFDTD

- They have only rarely been studied in the mid-IR
- Near field of metamaterials has rarely been studied
- By facet patterning a metamaterial onto a QCL, we hope to be able to study their unique properties, as well as generating a host of useful effects for QCL operation
- A split ring resonator (SRR) array on a QCL facet can be used for beam shaping and strong near field enhancement amongst other potential uses

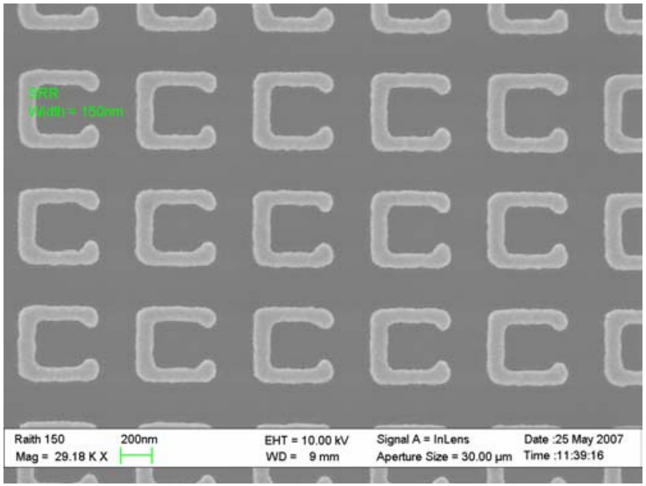
Metamaterials



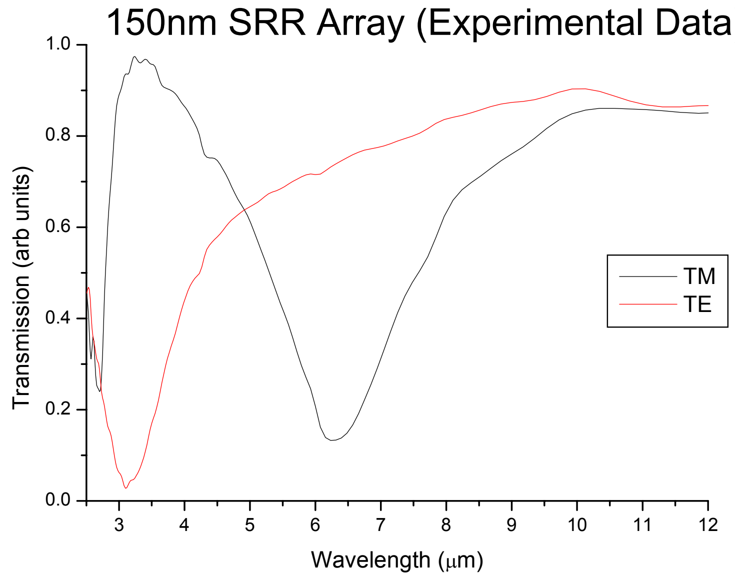
FDTD simulation of the near field enhancement in an SRR array

• Near field enhancement is comparable to the Antenna designs (~30×)
• A narrow 'beaming' far field is expected for the resonant frequency, with a much larger expected power than a beaming aperture
• Split ring resonators are patterned onto the facet by focussed ion beam milling, but first we looked at metamaterials on bare GaAs wafer (patterned by EBL)
• This shows us the expected response at the resonant wavelength

Metamaterials on GaAs



150nm arm width passive SRR array

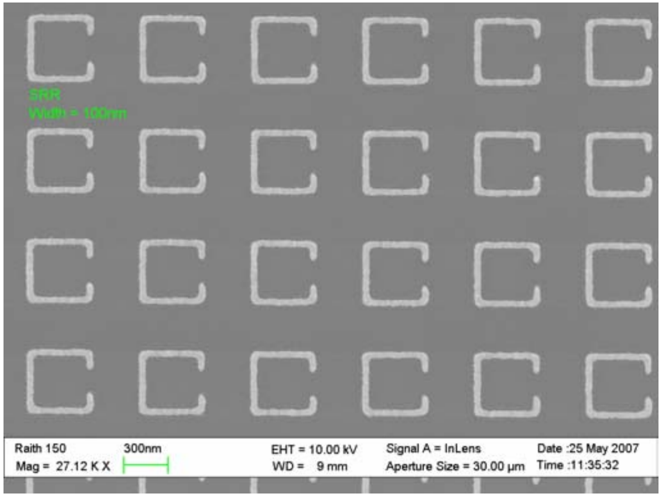


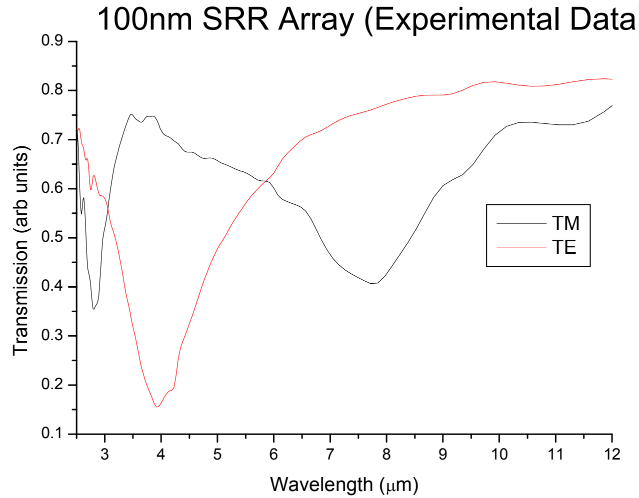
- The TM dip at 6.25µm is the LC resonance frequency, where the magnetic permeability takes negative values and the near field enhancement is largest
- The other dips in the TM and TE are different orders of plasmonic resonance associated with the SRR structure (the 'LC resonance' is also[5], but is associated with the SRR gap, leading to its unusual properties)

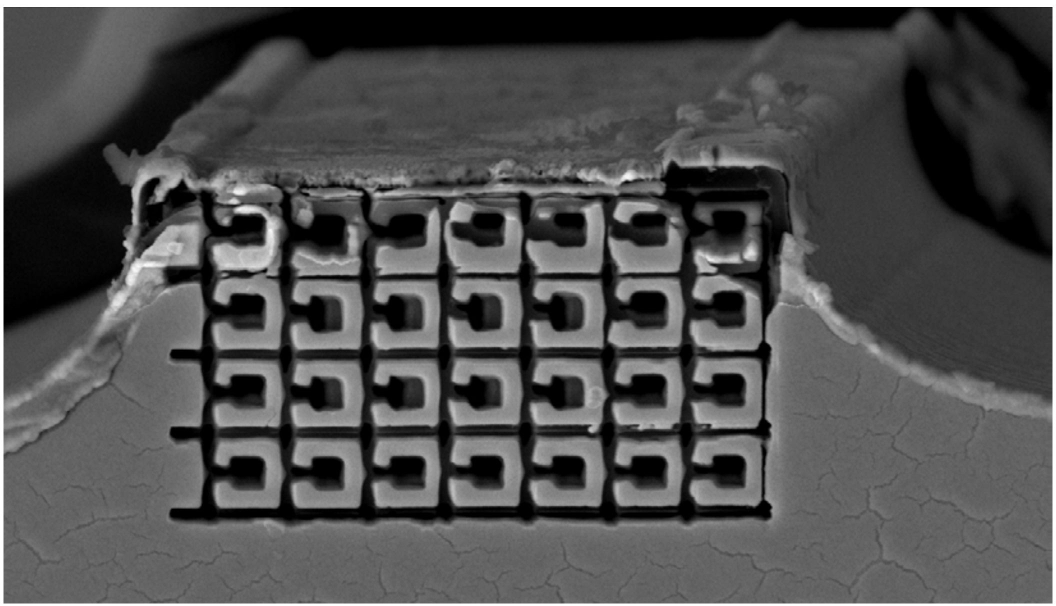
[5] – C. Rockstuhl et al, Vol. 14, No. 19 / OPTICS EXPRESS 8827 (2006)

Metamaterials on GaAs and QCLs

100nm arm width SRR array

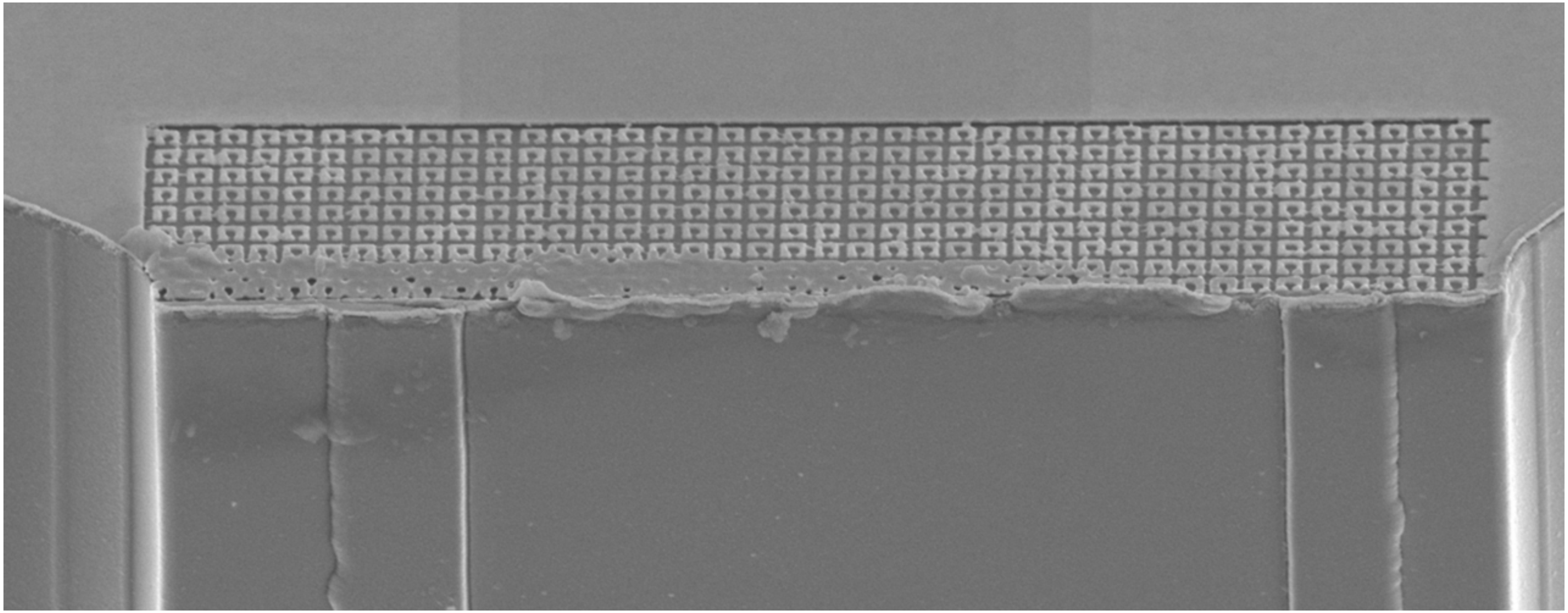






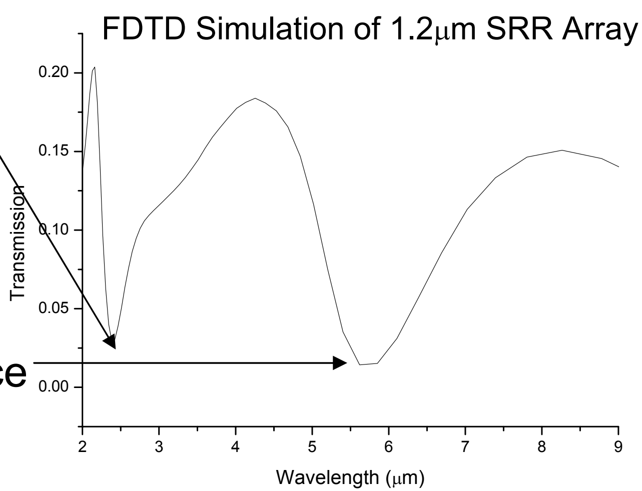
QCL with SRR patterned facet. The size and geometry of the SRRs is chosen so the emission wavelength corresponds to the LC resonance

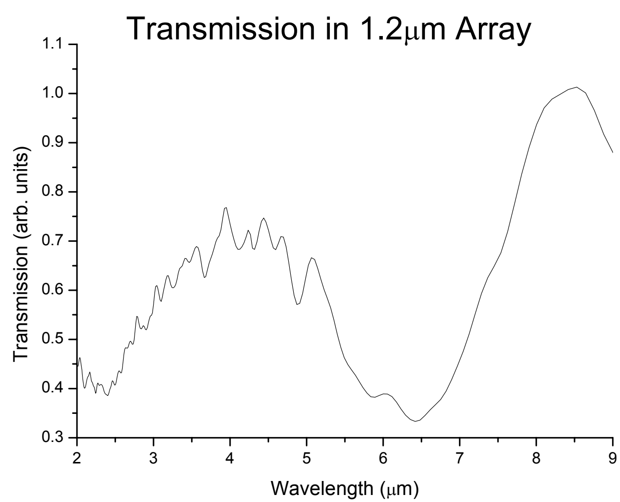
1.2μm SRR Array FIB Milled on QCL Facet



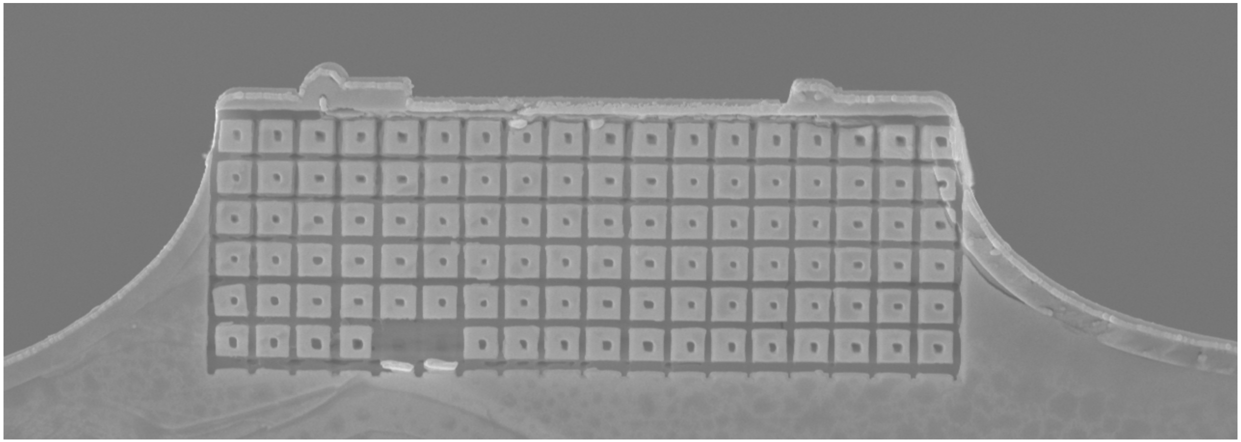
Plasmonic resonance

LC resonance

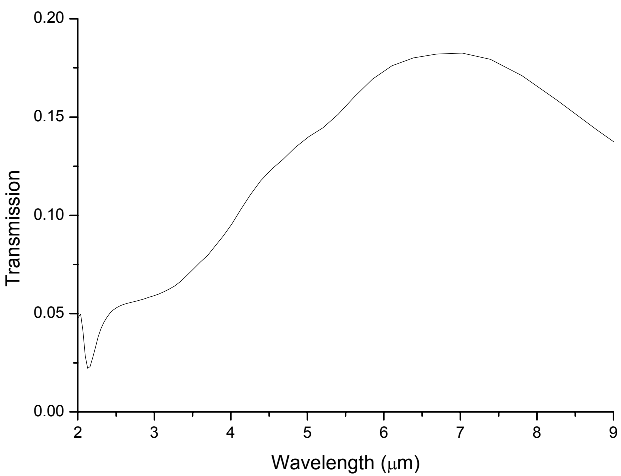




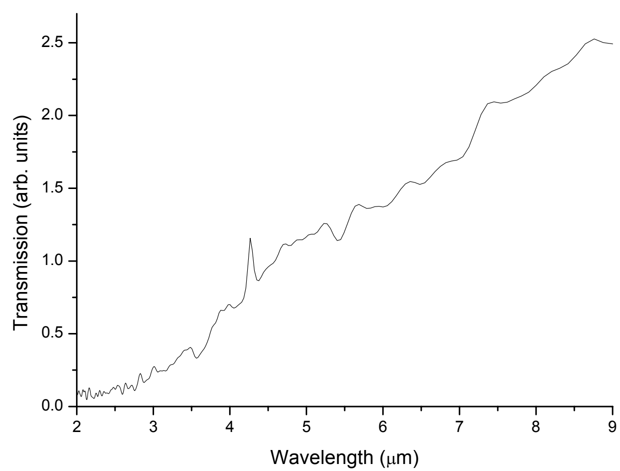
950nm Closed SRR Array FIB Milled on QCL Facet



FDTD Simulation of Closed 950nm SRR Array



Transmission from closed 950nm SRR Array



Conclusion

- Different types of antenna structures have been investigated, with the X-shape proving the most conducive to future use

- The a-snom probe alters the profile of the enhancement, and this seems to have a large dependency on the tip size

- Future work will include the characterization of the antenna structures with varying tip sizes

- Preliminary passive SRR-QCLs have been developed for transmission experiments (TE polarized), which show the same characteristics as for bare GaAs

- Future work is to look at the near and far field behaviour, including measurements with the a-SNOM