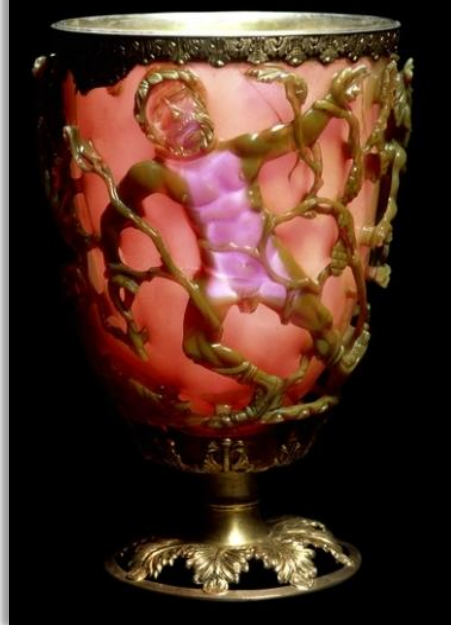


## BEYOND THE LENS OF THE LOOKING GLASS

Figure 1: Lycurgus cup [2]



Figure 2: Lycurgus cup [2]



In metamaterials we can exploit these effects to produce spectacular results. This becomes increasingly difficult in metamaterials designed for use in the visible spectrum (400-750nm) where the structures fabricated must have lengths of less than 100 nanometres

On an unremarkable page in the extraordinary book of technological evolution, artisans labour to produce an exquisite vessel, a gift by the priests of Rome to the leader of an empire. Centuries of scientific enterprise and craftsmanship culminate in a single vessel, a dull jade chalice which when presented to the sun blazes crimson. With the collapse of the empire, knowledge fades and the Lycurgus cup becomes an object of legend.

For almost 2000 years this vessel seemingly defied both logic and science. Then, in the early 21<sup>st</sup> century, a new facet of material science was discovered. These new materials manipulated light in interesting and 'impossible' ways.

They were termed metamaterials.

The Lycurgus cup is one of the earliest known and best preserved examples of a metamaterial. These materials allow for the construction of devices once relegated to the world of science fiction, devices such as hyperlenses, cloaks of invisibility and light circuits which have the power to revolutionise every aspect of our lives from communication and health to security and warfare.

While a distinct definition of a metamaterial remains contentious, common elements exist in all descriptions.

A metamaterial is a material which;

- 1). *gains its properties from its structure rather than its component materials*
- 2). *is a man-made material*

Just as the contours rather than the composition of the ocean-floor determine the shape of the waves above, metamaterials rely on structures such as wires and split-rings. In order for the metamaterial to function these structures must be much smaller than the waves they are designed to influence. Now imagine the seafloor is covered with an array of rocks and holes. If these objects are small enough they will not directly stop the wave but rather, induce currents and turbulence, bending and distorting the wave fronts as seen in Figure 3.



Figure 3: Waves passing over pebbles inducing currents which modify the original wave.



Figure 5 Fibre Drawing process

To overcome these difficulties a team of researchers at the Sydney Institute of Photonics and Optical Science (IPOS), led by Boris Kuhlmeiy, Maryanne Large and Simon Fleming are employing a technique more commonly used to manufacture fibre-optic cables.

Fibre Drawing is an established technology in the production of fibre-optic cables which are glass fibres used for high speed communication; the application of fibre drawing to the production of metamaterials however, is extremely novel. Unlike current techniques such as nanolithography or electron beam lithography which are expensive and slow, fibre drawing, if successful, would allow for the production of large quantities of metamaterial for a low cost.

Fibre drawing allows a pre-form to be easily modified when it has cm by cm dimensions, for example drilling holes and arranging metal fibres. This pre-form is then heated and stretched into a wire which is kilometres long and only micrometres in diameter as shown in Figure 5. The features of the cross section of the pre-form are retained but miniaturised as demonstrated in Figure 4. With fibre features around 20 nanometres in diameter light can be manipulated in astounding ways creating extraordinary metamaterials.

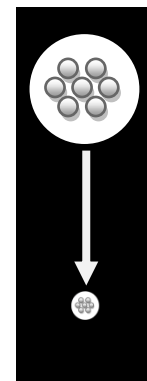


Figure 4 Cross section reduction

The distinction between Metamaterials and conventional materials however is not always clear,

for example while the calcite crystal in Figure 6 exhibits striking and unusual optical properties it is not classified as a metamaterial.

Calcite gains remarkable optical properties from an effect known as birefringence, which means it has different refractive indices for the different polarisations of light which pass through it. In the case of the crystal in Figure 6 there are two different refractive indices. When this Crystal is placed on a cross shape, the light passing through the crystal is bent in two slightly different directions resulting in two crosses being visible instead of one.

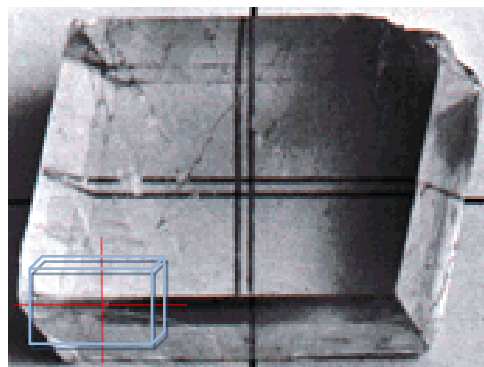


Figure 6 Calcite Crystal

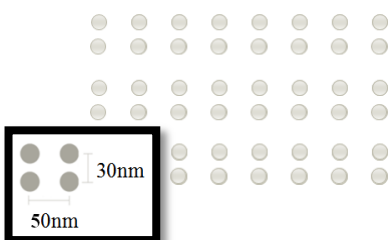


Figure 7 Metamaterial array

With the help of metamaterials we can enhance and refine this effect to create extreme birefringence. This can be done using an array of sliver nano-cylinders embedded in silica glass shown in Figure 7.

When Light approaches this structure from a horizontal direction (Figure 8), the electric fields interact with the closely spaced nano-cylinders and the light is reflected. In this direction the metamaterial behaves like a metal. In the vertical direction the light passes straight through the metamaterial unimpeded as shown in Figure 9. Therefore in this direction the metamaterial behaves like a transparent dielectric such as glass. Both Figures 8 and 9 depict the Electric field as it passes through the object.

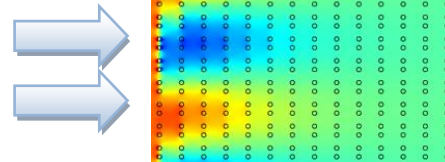


Figure 8 Horizontal Direction

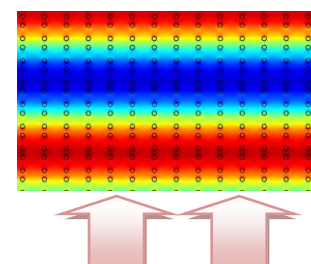
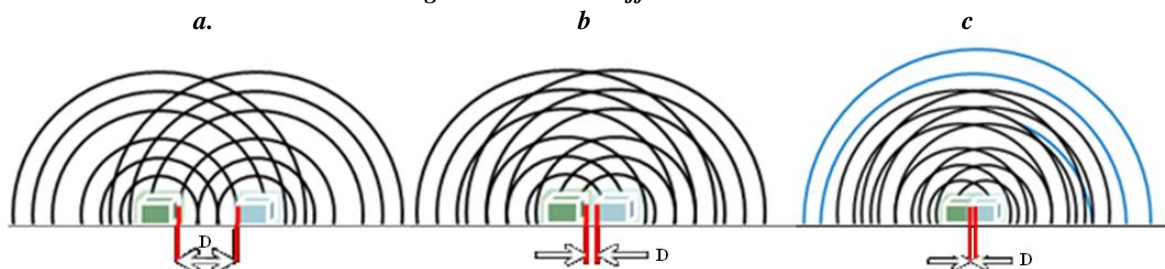


Figure 9 Vertical Direction

This extreme birefringence has practical applications in a device called the hyperlens. Hyperlenses are radical new devices which have the ability to observe objects and details that are physically impossible for conventional lens systems to detect.

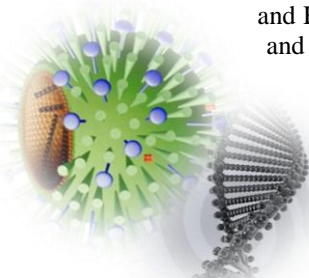
All devices which rely on geometrical lenses to manipulate light are termed ‘conventional’. Such systems are not only highly susceptible to defects within the lens; they possess a fundamental limit on their magnification ability, beyond which the collected information becomes useless. You can witness a similar effect through excessively ‘zooming in’ on a picture, eventually the entire screen will be filled with a square of one colour. When two objects are placed close together the electromagnetic radiation they emit interact to form complex interference patterns shown in Figure 10a. As the objects move closer together the patterns change (Figure 10b) eventually reaching a point where conventional imaging systems will see the two objects merge together to form one single object (Figure 10c). The distance between the two objects when this occurs is called the diffraction limit and is usually around half the distance of the smallest wavelength of radiation captured by the lens.

**Figure 10: The diffraction limit**



As the distances ( $D$ ) decrease conventional optical systems will see the two objects merge together to form one object. This distance is called the diffraction limit.

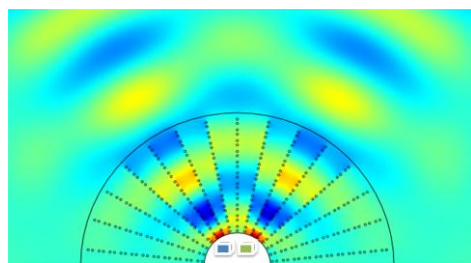
Because hyperlenses are not constrained by the diffraction limit, they can theoretically ‘see’ DNA and viruses allowing them to explore the interactions between cells and deadly viruses such as influenza and HIV. This gives them the potential to revolutionise our understanding of these interactions and provide a means of directly assessing the effectiveness of some types of medication.



**Figure 11 Virus and DNA models**

When an object is placed at the top of this metamaterial as shown in Figure 12 its electromagnetic radiation passes straight through in the vertical direction. However when the light diffracts or spreads it is reflected by the columns of nano-cylinders. Thus diffraction is limited by the distance between the 2 columns of nano-wires.

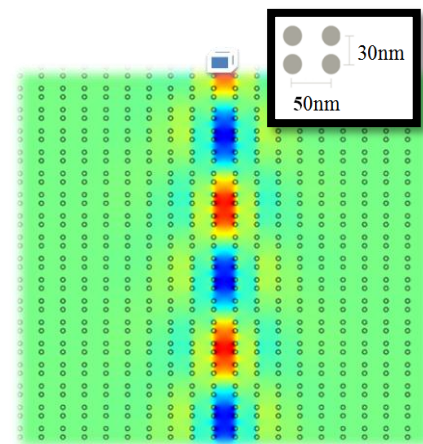
If the columns in Figure 12 are arranged in a semicircle as shown in Figure 13, a hyperlens is created.



**Figure 13 A Hyperlens**

Hyperlenses can ‘see’ these tiny objects by using extreme birefringence to limit the diffraction of the light. Using an identical structure to the one in Figure 7 the light passing through this structure in the horizontal direction is reflected while light approaching from the vertical direction is transmitted through the structure.

When an object is placed at the top of this metamaterial as shown in Figure 12 its electromagnetic radiation passes straight through in the vertical direction. However when the light diffracts or spreads it is reflected by the columns of nano-cylinders. Thus diffraction is limited by the distance between the 2 columns of nano-wires.



**Figure 12 A Metamaterial**

When two objects are placed closer together than the diffraction limit the hyperlens captures light from both of the objects before diffraction can allow the objects to merge. The light transmitted down the hyperlens is again unable to diffract. Because of the shape of the hyperlens when the light from the two objects emerge from the other end the objects appear further apart than the diffraction limit and therefore can be imaged by conventional systems.

A paper written in 2009 by Alessandro Tuniz and co-authors from the Sydney Institute of Photonics and Optical science concluded that using this array of silver nano-wires embedded in silica glass would create a functioning hyperlens. The Silver nano-wires used in the paper however have a melting point of 962°C and therefore cannot be drawn using the fibre drawing tower at the University of Sydney, which has a heating limit of only 850°C.

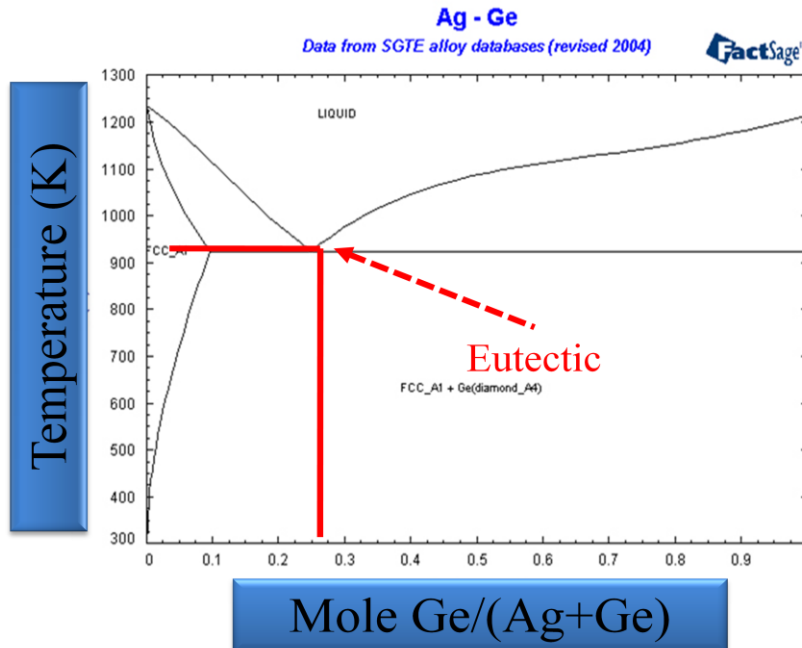


Figure 14 Phase diagram

To overcome this hurdle it was decided that silver alloys or more specifically the eutectic of silver alloys could be used as a substitute for pure silver. The eutectic point is a specific composition of metals at which the melting point of the alloy is much lower than the melting points of either of the two constituent metals as shown in the phase diagram, Figure 14. Also at the Eutectic, both metals transition from liquid to solid at the same time eliminating the appearance of unwanted nano-crystalline structures in the liquid phase which would be detrimental to the drawing process.

Matthew New-Tolley, a first year Physics student from the University of Sydney was tasked with finding appropriate alloys and then running simulations to determine how suitable these alloys were for use in a hyperlens.

Initially four alloys were studied; these alloys had to have a composition of silver greater than 20% at the eutectic because:

- Silver has excellent optical properties and
- Silver has already been used to create a hyperlens.

The four alloys were:

Silver/Aluminium  
Silver/Germanium  
Silver/Antimony  
Silver/Silicon

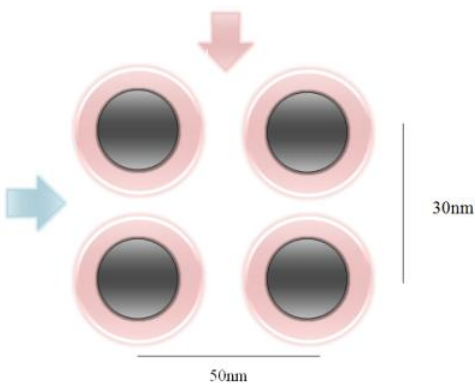


Figure 15 Simulation setup

These metal combinations were then tested to determine whether they would manipulate light in the ways needed to create a functioning hyperlens. For wires with these tiny diameters it is known that the constituent metals will separate in some way however the exact geometry of this separation is unknown.

The simulations were based on the assumption that the metals will separate into concentric shells.

The simulation consisted of two parts one with the light approaching from the horizontal direction the second where the light approached the structure from the vertical direction.

The results of the simulation are a graph of the scattering cross section against the wavelength.

The scattering cross section is a measure of the visibility of the cylinders and is a good indication of where in the visible electromagnetic spectrum the hyperlens will function most effectively.

A hyperlens constructed out of Silver-core silicon coated wires would function very well at wavelengths of around 405-425nm.

From Figure 16 the scattering cross section in Direction 1 is much higher which means that the wires are more visible and therefore behaving more like a reflective metal. When light approaches from Direction 2 the scattering cross-section is lower which means more of the light is being transmitted through the structure. This pattern confirms that this composition could be used to create a functioning hyperlens.

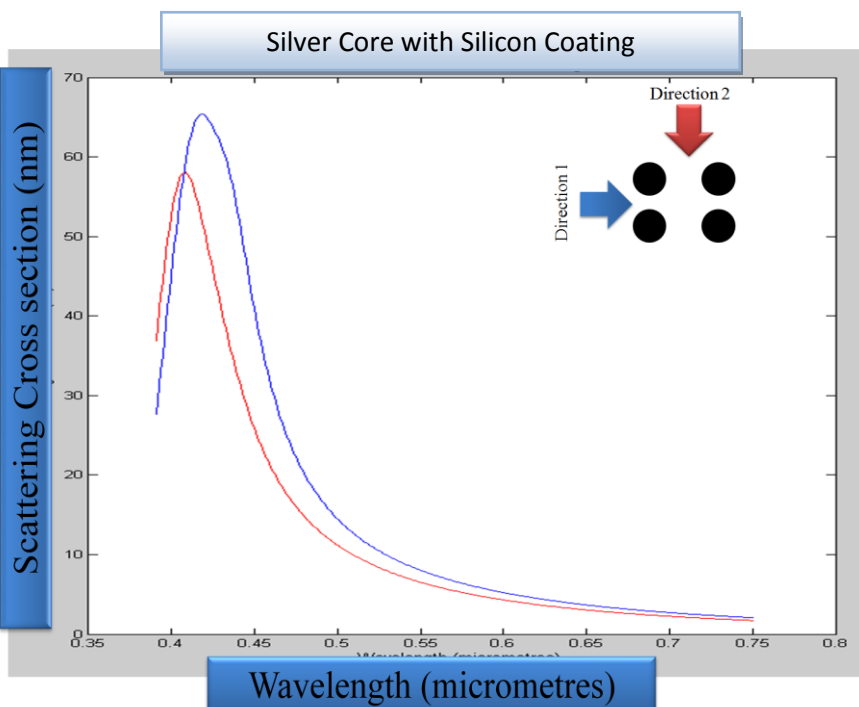


Figure 16 Results Silver Core with Silicon Coating

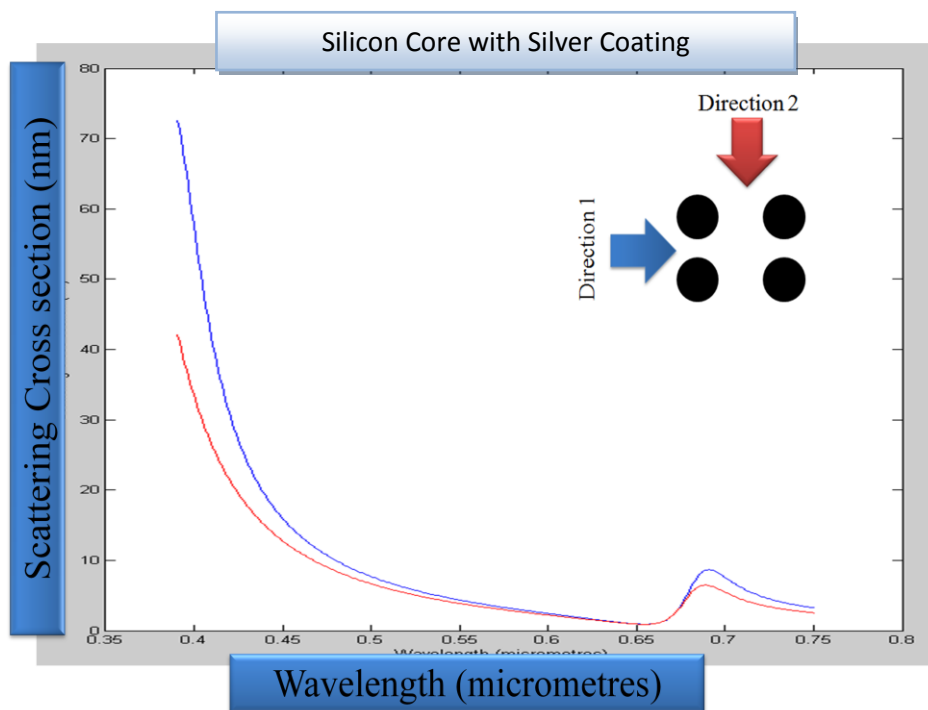


Figure 17 Results Silicon Core with silver Coating

Another interesting result came from the simulation of the inverse geometry, with the Silicon on the inside of the cylinder this time, coated in Silver. This combination resulted in the formation of an interesting second resonance around the 675nm mark which is still within the optical range. This result is interesting as this occurred in none of the previous simulations, alloys of silver and aluminium produced resonances which were slightly too low for the optical range and while the alloys of Germanium created resonances within the optical range they were far weaker than those seen by Silicon/silver alloys. Antimony has very similar properties to

Arsenic including its toxicity and as a result was discarded for this research.

These simulations demonstrated the dependence the optical properties of an alloy on the way the metals choose to separate: With silver coating a silicon core, a second resonance was observed at a much longer wavelength than the inverse which produced a resonance around the 410nm wavelength. By far the most effective and interesting results were that of the silver and silicon as both sets of simulations produced a resonance within the optical range. Most importantly, these simulations show silver alloys with melting points within the range of the University of Sydney's drawing tower can in principle be used to fabricate hyperlenses, bringing them one step closer to reality

Researcher's at the Institute of Photonics and Optical Science are working on the very boundaries of our knowledge, asking questions and providing answers which reveal startling information and force us to redefine the boundaries of impossibility. The Roman artisans scratched this boundary creating on object so revolutionary, it could transcend time and 2 millennia later, re-shape the world in which we live.

By Matthew New-Tolley

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I would like to thank Dr Boris Kuhlmeier for all of his guidance and patience throughout this semester. I would also like to extend this thanks to Maryanne Large and Alessandro Tuniz for all of their advice and constructive criticism, it helped a-lot!

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Thanks,

Matt

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