METAMATERIALS, METALENSES AND BEYOND

For thousands of years, humans have been making optical components by melting, casting, grinding, and polishing commonplace materials. Manufacturing techniques borrowed from the semiconductor industry are now being used to make ultrathin ‘metalenses’, which could slim down cameras still further, and even allow handheld devices to sense all kinds of things beyond the visible spectrum. Dr Eric Plum from the University of Southampton explains how these have developed.

A metalens closeup: scanning electron microscope image of a meta-optical element designed and manufactured by NIL Technology, made up of arrays of pillars smaller than 100 nm in height. The variation in diameter of the pillars slows light by different amounts © Image courtesy of NIL Technology.
Did you know?

- Most current smartphones have a stack of six or seven lenses in their cameras
- Metallenses can be 100x thinner than a human hair, and focus light with dimensions smaller than the diffraction limit of light
- Microscopes, or simply correcting near-sightedness or perhaps a kind of sunglass).
- The Roman Emperor Nero was even said to have used a device in which individual nanowires can be more independently by electrical currents. Although the device shown is a proof of concept, with careful engineering, similar metamaterials could be used as spatial light modulators (like those that manipulate light in projectors) for creating holographic videos. Structures like this have been shown to respond to temperature, electric or magnetic fields, sound, and even light. This provides an opportunity to develop smart materials and sensors typical for applications like magnetic field sensing or radiation detection with very high spatial resolution.

The Lightest Lenses Yet

Today however, the metallenses advance that’s on the brink of making a commercial impact is the cloaking materials, which could transform the size, weight and complexity of optical systems. In both cameras and phones are to continue on their trajectory of miniaturisation, conventional glass or plastic lenses won’t cut it. As it illustrated in the ‘slowing down light’ figure (above), these reflective lenses work by slowing down and therefore bending wavefronts of light, which requires them to be thick in certain regions. Shining a lens down to an essentially flat surface requires a different approach. In a typical metamaterial, a surface (such as a flat, ultrathin piece of glass) is covered in nanoscale pillars. The size of the pillar determines how much it will delay light. To be able to delay the light field efficiently, the pillars need to be made from a material with a high refractive index, while low absorption is needed to make a transparent lens. Typical metamaterials for visible light use titanium dioxide (widely used...
Making metalenses: metalenses can be prototyped using electron beam lithography (left), which offers the flexibility to try many different designs:
1. A beam of electrons exposes a layer of resist where pillars should be formed.
2. The exposed resist is washed away.
3. The pillar material is deposited with sufficient thickness to fill all the gaps and produce a flat surface.
4. Excess pillar material is etched away.
5. The remaining resist is removed and the metalens remains.

Right: gallium nitride pillars made by electron beam lithography at K’un Nanotechnology (Glasgow). Metalenses can be mass produced by either using the pillars as a stamp (called nanoprint lithography) or by replotting this step with deep UV lithography, for example by STMicroelectronics (Croix, France).

Beating the diffraction limit: waves have alternating crests (yellow) and troughs (red) that repeat after a distance known as wavelength, \( \lambda \). Light waves consist of an oscillating electric (and magnetic) field, with crests and troughs corresponding to the largest field in opposite directions. If light waves pass through a pair of slits, they will form a series of dark lines (crest meets trough, white) and bright lines (crests or troughs meet, orange). The lines become narrower as the slits are moved further apart until they reach a minimum width of half a wavelength: the diffraction limit. Smaller, arbitrarily small, lines or focal spots may be achieved by combining several pairs of slits.

Shrinking down diagnostics and VR
The shared vision of thin, smartphone cameras and their enormous market potential has accelerated the transition of metalenses from university labs towards mass manufacture. Startups such as Metalenz and NIL Technologies (NILT), large manufacturers such as Samsung, and Silicon Valley companies such as Camplean have powerful capabilities beyond traditional optical lenses as they have completely flat surfaces, reduced thickness, and improved quality compared to classic refractive lenses, explains Theodor Nielsen, NILT’s CEO and Founder. “They will be a game-changer for optical applications in consumer products, smartphones, and augmented, virtual and mixed reality devices.”

The growing industry traction in these areas is likely to act as a catalyst for the wider application of metalenses and metamaterials, resulting in new applications altogether. Beyond making smartphone cameras, metalenses can have features that oscillate with a wavelength of half a micrometre thick can direct light from a point source to a sensor. It can even be used to generate a hologram with any desired distribution of light, for example, as a security feature for bank notes or passports. But metalenses can be made by moulding and polishing glass or plastic, metalenses and metamaterials can be made with the same manufacturing techniques as the semiconductor industry uses to make computer chips.

Zooming in on viruses
Another major challenge for conventional lenses is resolution. Much of our understanding of the biological world is based on what we can see through optical microscopes. Conventional lenses can focus light to a spot that is approximately half a wavelength in size, which is about 250 nm for visible light. This so-called ‘diffraction limit’ is what prevents us from seeing viruses and proteins using light microscopes, as the resolution isn’t high enough. Focusing light into smaller spots is the key for seeing these smaller objects. (Other imaging techniques allow imaging of things this size, but you must undergo harsh treatments such as being crystallised or cryogenically frozen. One example is electron microscopy, as seen in images in this article, which requires samples to be placed in a vacuum.)

Fortunately, metalenses may be engineered to circumvent the diffraction limit, enabling light – or any other wave – to be concentrated in much smaller spots. The key to beating the diffraction limit is a concept known as superoscillations. The sum of slowly oscillating waves can have features that oscillate fast.

Beating the diffraction limit (above) shows an example: light waves passing through slits in a screen, forming an interference pattern of bright and dark lines. The lines generated by a pair of slits have a width of at least half of the wavelength. However, if we combine pairs of slits, the superposition of the light fields can have much smaller features. Careful engineering of such structures allows this light to be concentrated into lines or spots of much smaller size.

The final figure (next page) shows a superlens consisting of concentric ring slits in an aluminium film, which concentrates red light into a spot of less than 200 nm diameter. The price to pay is that tiny focal spots will only contain some of the incident light, but that has not prevented the development of super resolution microscopy for beyond the diffraction limit, for biology and beyond. Indeed, recent experiments at the Nanyang Technological University (Singapore) and at the University of Southampton demonstrate that tiny superoscillations can be used to create an ‘optical ruler’ that detects movements as small as 1 nm, corresponding to a resolution of 1,700 (where lambda, \( \lambda \), is the wavelength). This indicates even atomic-scale resolution may be within reach.

Biography
Dr Eric Plum is a Principal Research Fellow at University of Southampton. After studies in Aachen (Germany), Southampton and US, he joined Southampton’s Optoelectronics Research Centre, where he has been leading research on metamaterials since 2010. He is a Marconi Young Scholar, Institute of Physics prize recipient, and has been a Fulbright Scholar and Advanced Leverhulme Trust Fellow.