Plasmonics

- The long wavelength of light (≈ μm) creates a problem for extending optoelectronics into the nanometer regime.

- A possible way out is the conversion of light into plasmons.

- They have much shorter wavelengths than light and are able to propagate electronic signals.

What is a Plasmon ?

A plasmon is a density wave in an electron gas. It is analogous to a sound wave, which is a density wave in a gas consisting of molecules.

Plasmons exist mainly in metals, where electrons are weakly bound to the atoms and free to roam. The free electron gas model provides a good approximation (also known as jellium model).

The electrons in a metal can wobble like a piece of jelly, pulled back by the attraction of the positive metal ions that they leave behind.

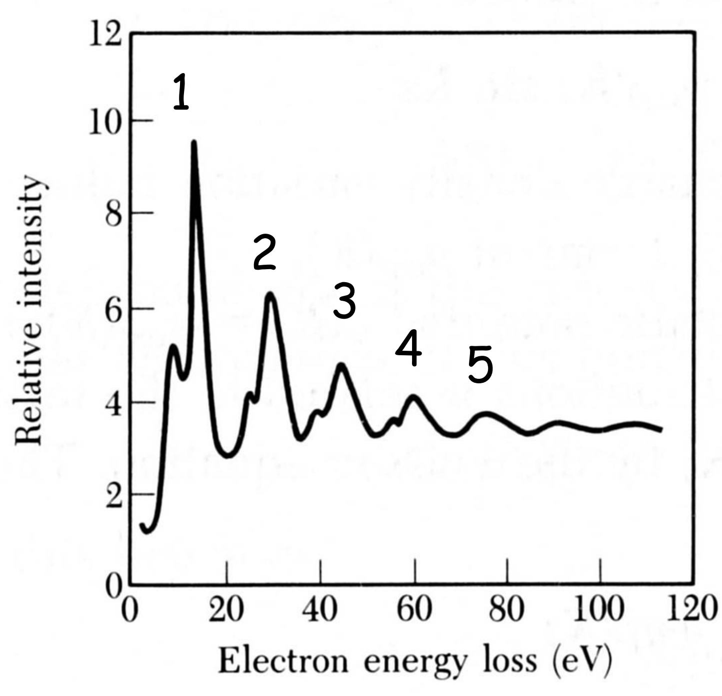
In contrast to the single electron wave function that we encountered already, a plasmon is a collective wave where billions of electrons oscil-late in sync.

The Plasmon Resonance

Right at the plasmon frequency ω_p the electron gas has a resonance, it oscillates violently. This resonance frequency increases with the electron density n, since the electric restoring force is proportional to the displaced charge (analogous to the force constant of a spring). Similar to an oscillating spring one obtains the proportionality:

$$\omega_p \propto \sqrt{n}$$

The plasmon resonance can be observed in electron energy loss spectroscopy (EELS). Electrons with and energy of 2 keV are re-flected from an Al surface and lose energy by exciting 1, 2, 3,... plasmons. The larger peaks at multiples of 15.3 eV are from bulk plasmons, the smaller peaks at multiples of 10.3 eV from surface plasmons.

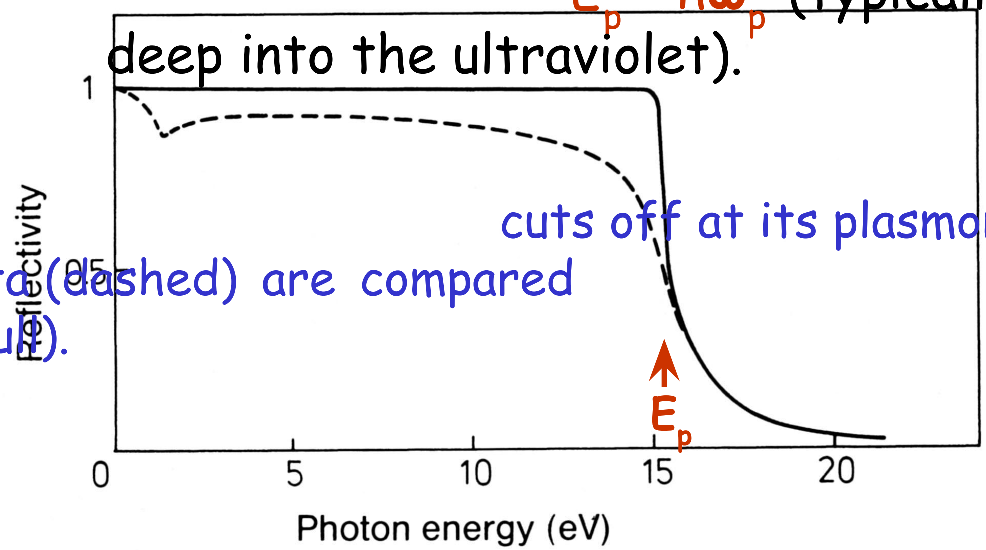


Why are Metals Shiny ?

An electric field cannot exist inside a metal, because metal electrons react to it by creating an opposing screening field (Lect. 2, Slide 13). An example is the image charge, which exactly cancels the field of any external charge. This is also true for an electromagnetic wave, where electrons respond to the changing external field and screen it at any given time. As a result, the electromagnetic wave cannot enter a metal and gets reflected back out.

However, at high frequency (= high photon energy) there comes a point when the external field oscillates too fast for the electrons to follow. Beyond this frequency a metal loses its reflectivity. The corresponding energy is the plasmon energy $E_p = \hbar\omega_p$ (typically 10-30 eV, deep into the ultraviolet).

The reflectivity of aluminum cuts off at its plasmon energy. Data (dashed) are compared to the electron gas model (full).



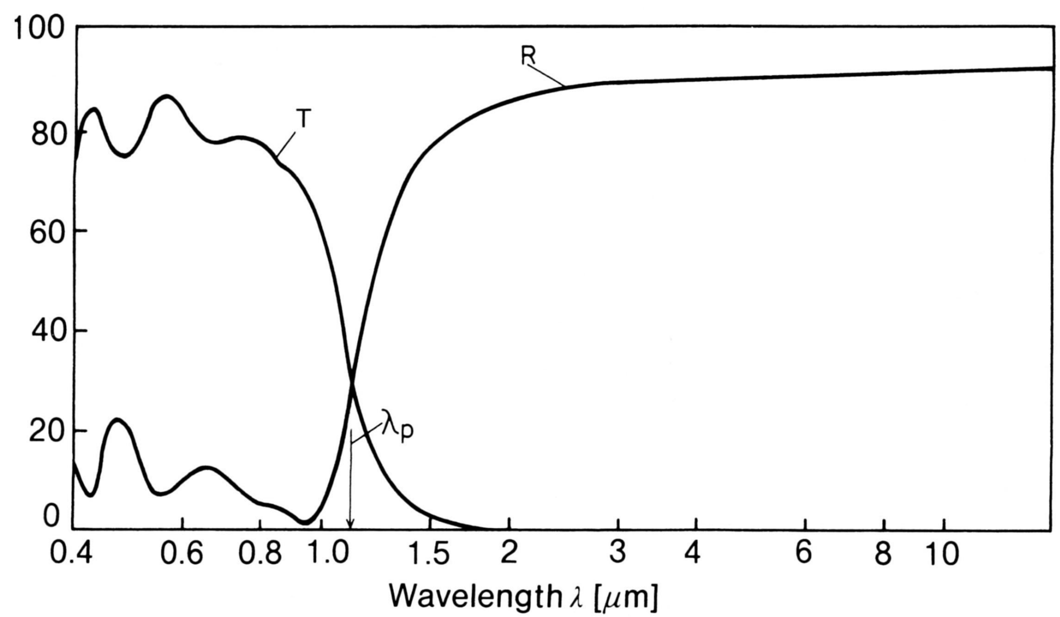
Plasmons and Energy-Saving Window Coatings

The reflectivity cutoff at the plasmon energy can be used for energy-saving window coatings which transmit visible sunlight but reflect thermal radiation back into a heated room.

To get a reflectivity cutoff in the infrared one needs a smaller electron density than in a metal. A highly-doped semiconductor is just right, such as indium-tin-oxide (ITO). We encountered this material already as transparent front electrode for solar cells and LCD screens.

An ITO film transmits visible light and reflects thermal infrared radiation, keeping the heat inside a building.

R = Reflectivity T = Transmission



Low-Dimensional Plasmons in Nanostructures

Lecture 8 showed how single electron waves become quantized by confinement in a nanostructure. Likewise, collective electron waves (= plasmons) are affected by the boundary conditions in a thin film, a nano-rod, or a nano-particle.

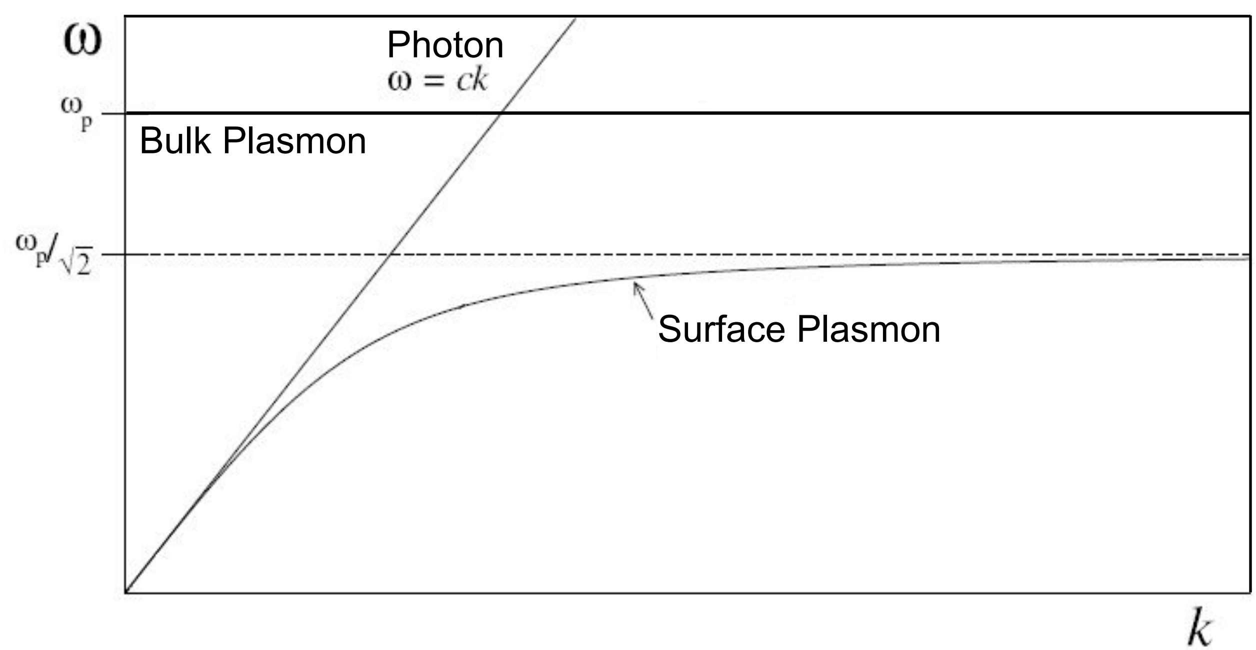
Plasmons in metal nanoparticles are often called Mie-resonances, after Gustav Mie who calculated them hundred years ago. Their resonance energy and color depend strongly on their size, similar to the color change induced in semiconductor nanoparticles by confinement of single electrons (Lecture 9, Slides 6,7). In both cases, smaller particles have higher resonance energy (blue shift).

Nanotechnology in Roman Times: The Lycurgus Cup

Plasmons of gold nanoparticles in glass reflect green, transmit red.

Quantum Numbers of Plasmons

Like any other particle or wave in a (crystalline) solid, a plasmon has the energy E and the momentum **p** as quantum numbers, or the circular frequency $\omega = E/\hbar$ and the wavevector $\mathbf{k} = \mathbf{p}/\hbar$. One can use the same E(**k**) plots as for single electrons (Lecture 7b).



Coupling of Light and Plasmons

To combine optoelectronics with plasmonics one has to convert light (photons) into plasmons. This is not as simple as it sounds.

Bulk plasmons are longitudinal oscillations (parallel to the propa-gation direction), while photons are transverse (perpendicular to the propagation). They don't match.

Surface plasmons are transverse, but they are mismatched to photons in their momentum. The two E(k) curves never cross. It is possible to provide the necessary momentum by a grating, which transmits the wavevector $\Delta k = 2\pi/d$ (d = line spacing) .

Attenuated Total Reflection

Another method to couple photons and surface plasmons uses attenuated total reflection at a metal-coated glass surface. The exponentially damped (evanescent) light wave escaping from the glass can be matched to a surface plasmon (or thin film plasmon) in the metal coating. This technique is surface sensitive and can be used for bio-sensors.

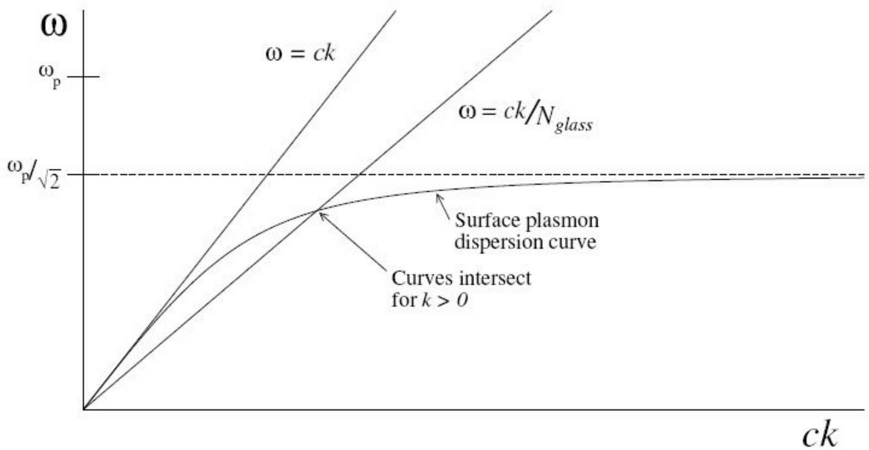
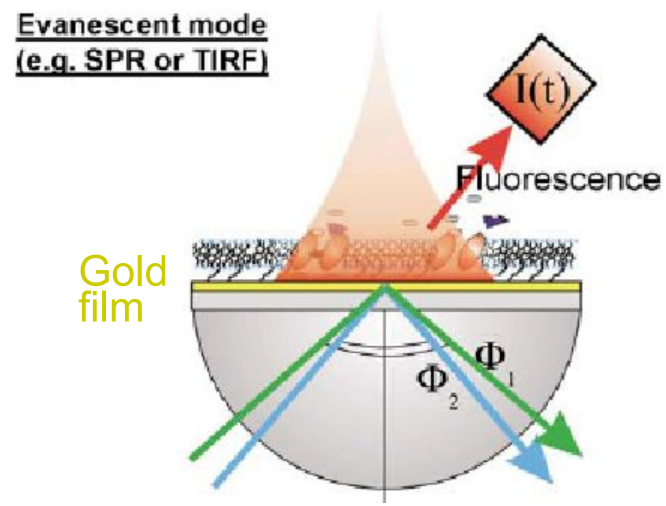


Figure 2: Dispersion curves for surface plasmons, air ($\omega = ck$) and glass ($\omega = ck/N_{glass}$, assuming N_{glass} is independent of wavelength). Note that the curves do not intersect for air and plasmons, indicating that plasmons cannot be excited from light propagating from air to the metal surface.



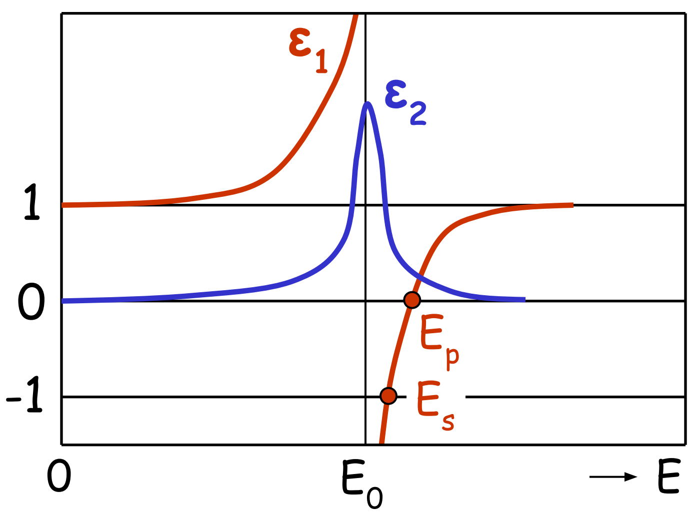
Plasmons and the Dielectric Constant ε

The dielectric constant is a complex number: $\varepsilon = \varepsilon_1 + i\,\varepsilon_2$

The real part ε_1 describes refraction of light,
The imaginary part ε_2 describes absorption.

The bulk plasmon occurs at an energy E_p where $\varepsilon_1 = 0$,
the surface plasmon occurs at an energy E_s where $\varepsilon_1 = -1$.

(More precisely: $\mathrm{Im}[1/\varepsilon]$ and $\mathrm{Im}[1/(\varepsilon+1)]$ have maxima.)

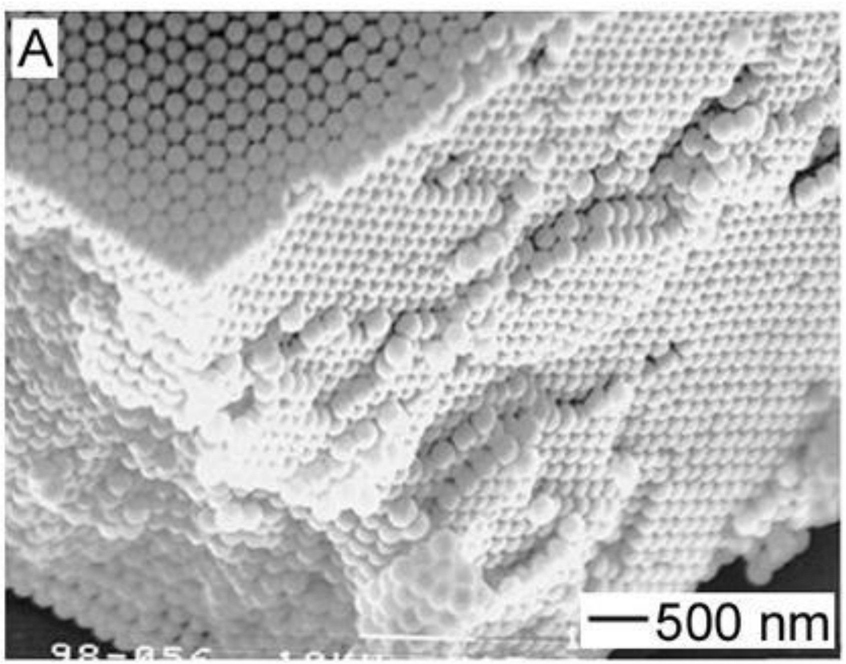


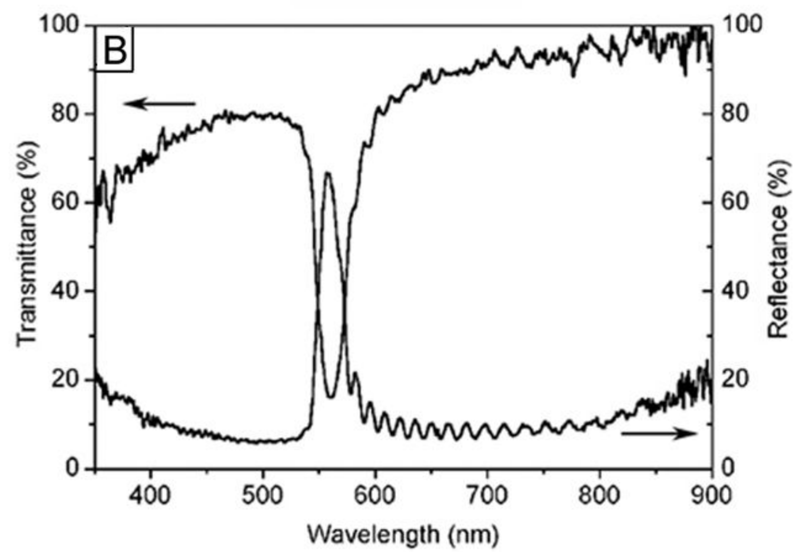
Typical behavior of the dielectric constant versus energy E for a solid with an optical transition at $E=E_0$. A metal has $E_0=0$.

Photonics

In photonics one tries to manipulate the dielectric constant via nanostructured dielectric materials ("metamaterials").

Particularly interesting is a gap in the E(k) relation of photons, analogous to the band gap of electrons in a semiconductor. The photonic band gap causes total reflection of light in all directions.

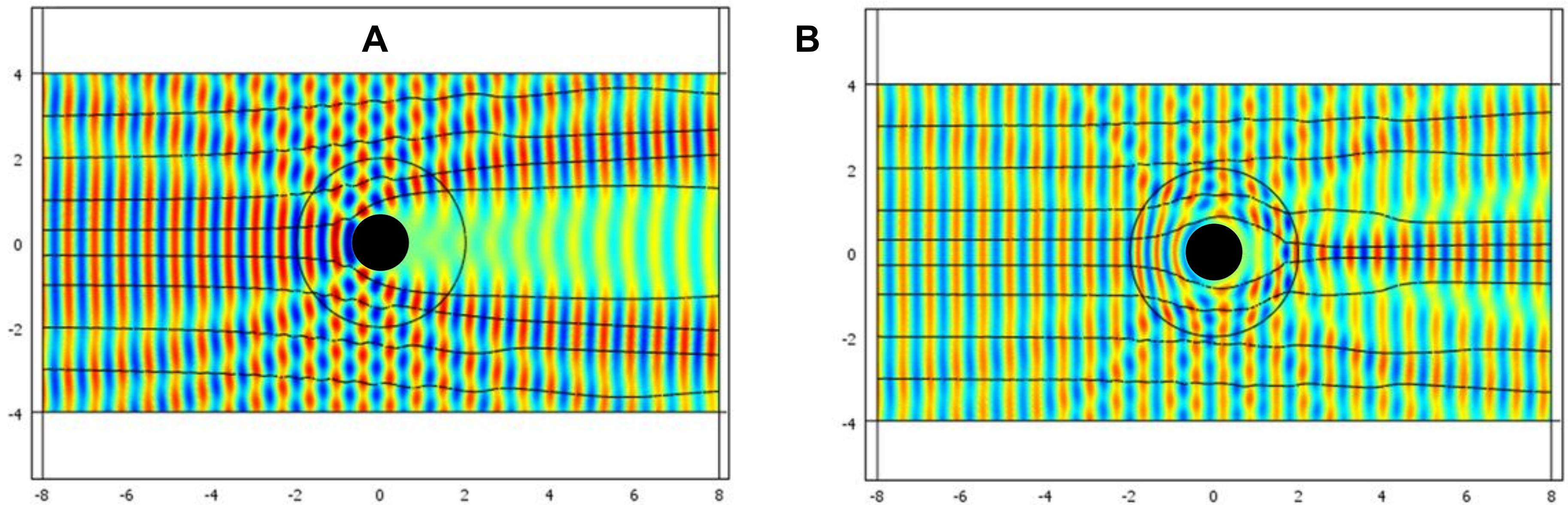




An artificial crystal lattice made from polystyrene beads (similar to an opal, an iridescent gemstone). The photonic band gap causes a reflectance maximum.

Cloaking: Making an Object Invisible

Surrounding an object with a material having the right kind of dielectric properties (negative refractive index) can make the object invisible.



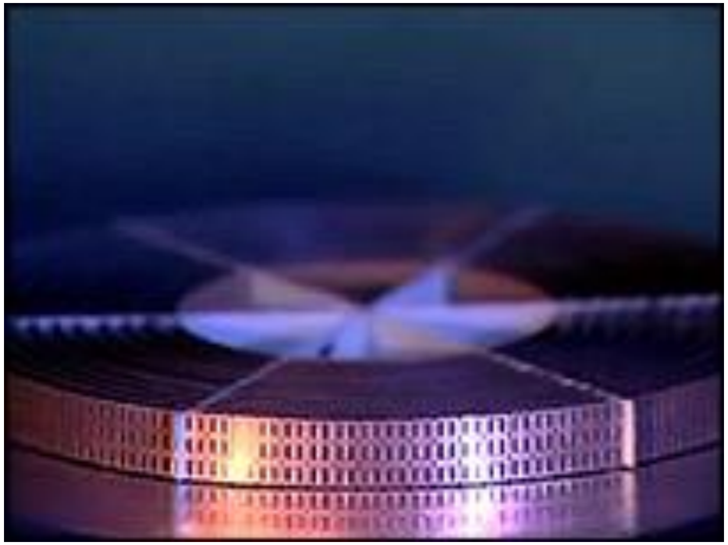
Cloaking simulation in two dimensions:

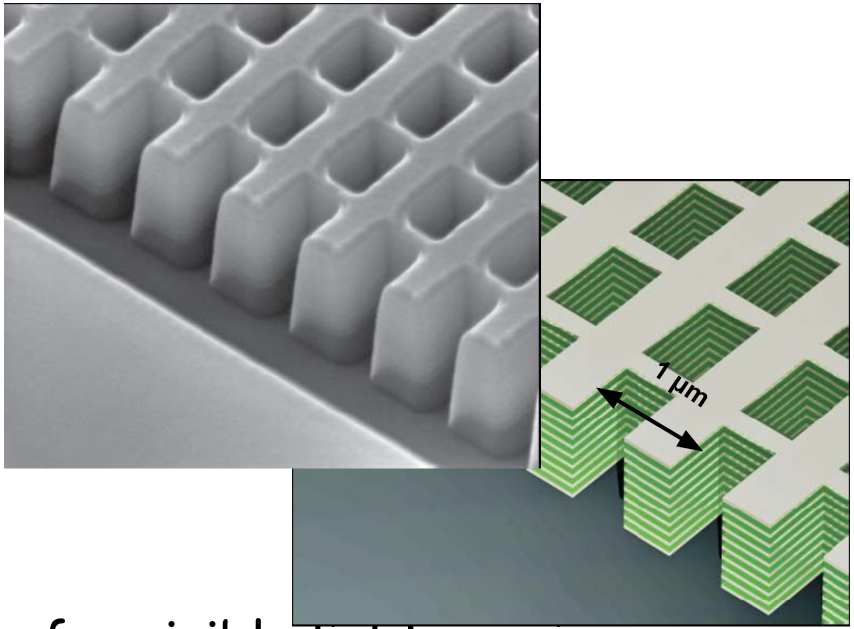
A. The black disc blocks the light coming from the left and reflects it back, leaving a shadow towards the right (green/yellow).

B. The surrounding ring of cloaking material guides the light around the disc and thereby fills in the shadow.

Actual Metamaterials

Most metamaterials with negative refractive index have been made for microwaves (below left). Such devices are interesting for making an airplane invisible to radar (wavelength ≈ 3 cm).



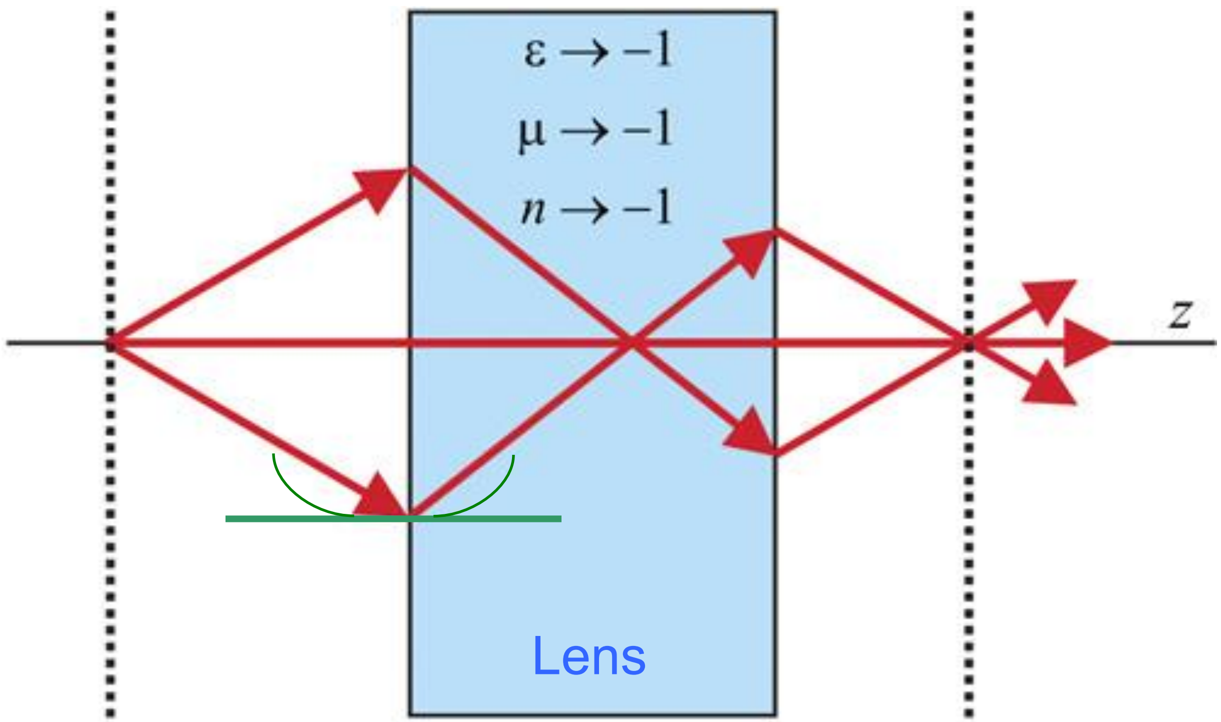


To produce analogous metamaterials for visible light requires nanotechnology with structures small compared the wavelength of light (above right). Even with that under control, it is hard to cloak an object at all wavelengths. Metamaterials are active only near a resonance, which occurs at a particular wavelength.

The Perfect Lens

A medium with refractive index $n = -1$ acts as perfect lens.

Since $n = \sqrt{\varepsilon \mu}$, one expects both ε and μ (magnetic permeability) to be negative.



Negative n refracts light towards the same side of the normal (not the opposite side).