Plasmonics: optics at the nanoscale

…Albert Polman and Harry A. Atwater

In photonics, metals are not usually thought of as being very useful, except perhaps as mirrors. In most cases, metals are strong absorbers of light, a consequence of their large free-electron density. However, in the miniaturization of photonic circuits, it is now being realized that metallic structures can provide unique ways of manipulating light at length scales smaller than the wavelength.

Maxwell's equations tell us that an interface between a dielectric (e.g. silica glass) and a metal (e.g. Ag or Au) can support a surface plasmon (SP). An SP is a coherent electron oscillation that propagates along the interface together with an electromagnetic wave. These unique interface waves result from the special dispersion characteristics (dependence of dielectric constant on frequency) of metals. What distinguishes SPs from 'regular' photons is that they have a much smaller wavelength at the same frequency. For example, a HeNe laser, whose free-space emission wavelength is 633 nm, can excite an SP at a Si/Ag interface with a wavelength of only 70 nm. When the laser frequency is tuned very close to the SP resonance, SP wavelengths in the nanometer range can be achieved. The short-wavelength SPs enable the fabrication of nanoscale optical integrated circuits, in which light can be guided, split, filtered, and even amplified using plasmonic integrated circuits that are smaller than the optical wavelength.

The reduction in wavelength comes at a price: SPs are often lossy. One way to achieve long propagation lengths is to use very thin metal films. In this case, SPs on both surfaces of the metal film interact, and both a symmetric and an asymmetric field distribution can exist. One of these modes has low loss and, for metal films as thin as 10 nm, centimeter propagation lengths can be achieved for SPs in the infrared. At a given frequency, the SP wavelength is strongly dependent on the metal thickness. Thus, the plasmonic integrated circuit engineer has an extensive toolbox, including choice of metal (dispersion), metal thickness, and excitation frequency.

When a light source such as a luminescent quantum dot or dye molecule is placed close to a metal, it can excite an SP through a near-field interaction. With a light-emitting diode (LED) embedded in a plasmonic structure, SPs can be electrically excited. Such SPs may serve as an alternative to overcome the information bottlenecks presented by electrical interconnects in integrated circuits. Coupling to SPs can also enhance the extraction efficiency of light from LEDs. Applications of SPs in solid-state lighting and lasing are just appearing, but it may be that traffic lights are composed of SP LEDs in a few years time!

Metallic nanoparticles have distinctly different optical characteristics than SPs at planar interfaces. Nanoparticles show strong optical resonances, again because of their large free-electron density. As a result, a plane wave impinging on a 20 nm diameter Ag particle is strongly 'focused' into the particle, leading to a large electric field density in a 10 nm region around the particle. Ordered arrays of nanoparticles can possess even further enhanced field intensities as a result of plasmon coupling between adjacent particles. By varying nanoparticle shape or geometry, the SP resonance frequency can be tuned over a broad spectral range. For example, Au ellipsoids or silica colloids covered with an Au shell show resonances that coincide with the important telecommunications wavelength band. The ability to achieve locally intense fields has many possible applications, including increasing the efficiency of LEDs, (bio-)sensing, and nanolithography.

Arrays of metal nanoparticles can also be used as miniature optical waveguides. In linear chain arrays of nanoparticles, a plasmon wave propagates by the successive interaction of particles along the chain. The propagation length is small (~100 nm), but may be increased by optimizing particle size and anisotropy. What makes these nanoparticle array waveguides attractive is that they provide confinement of light within ~50 nm along the direction of propagation, a 100-fold concentration compared to dielectric waveguides.

A very peculiar effect occurs in metal films with regular arrays of holes. Here too, local field enhancements are predicted to occur, now along the holes. These lead to much larger optical transmission through the holes than expected, based on consideration of their geometric areas. The precise role of SPs in these effects is still the subject of lively scientific debate, but applications of the enhanced transmission characteristics in nanoscale optical storage appear promising.

It is clear that there is a vast array of plasmonic concepts still waiting to be explored, with applications spanning (bio-)sensing, optical storage, solid-state lighting, interconnects, and waveguides. Indeed, it appears that metals can shine a bright light toward the future of nanoscale photonics.

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