Plasmonics: Surface Plasmon Optics and Circuitry

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Alchemists have utilized surface plasmons from gold colloids for centuries to create bold red, blue, and purple colors in glass.[1] Yet the phenomenon creating the nanoparticle's brilliant optical properties was not recognized until the late 19th and early 20th centuries by Faraday[2] and Mie.[3] Furthermore, the science behind the generation and manipulation of surface plasmons in both the alchemist's nanoparticles and, more recently, thin metal films has received great attention in the past few decades. As better control of nanometer-sized structures has improved with the expansion of the "nanotechnology thrust," the interest of surface plasmons in optical circuits below the diffraction limit has grown rapidly. This new field termed plasmonics[4] shows promise in simulated circuits[4-7] with some realized components[7-9] already showing progress.

Plasmonics holds several advantages over current electrical circuits and currently researched wavelength-regime optical circuits for several reasons. First, plasmonics would allow for conduction of both optical and electrical signals if the metal film is imbedded in a dielectric.[7] Also, surface plasmon optical circuits are more desirable than wavelength-regime optical circuits because the size of components in the circuit can be smaller than the diffraction limit ($\lambda/2$). Standard wavelength optical signals cannot propagate through structures smaller than this limit while surface plasmons can. Finally, due to the surface-coupled nature of surface plasmons, they are limited to two dimensions, allowing for easier directional control of sub-wavelength optical signals.

There are two methods currently being investigated for plasmonic devices: one using transmission of localized surface plasmon (LSP) dipoles between nanoparticles[4-6] (Figure 1A), and the other directing the propagation of surface plasmon polaritons (SPP) in thin metal films[7-9] (Figure 1B). The first method uses a generated oscillating dipole mode for transmitting energy from one particle to another of identical size and appropriate spacing. This method, therefore, requires precise control over nanoparticle size and alignment for the realization of plasmonic devices using this scheme. The latter method utilizes nanostructures in the form of protrusions or holes in metal films to guide SPPs via reflection off or transmission through these structures.

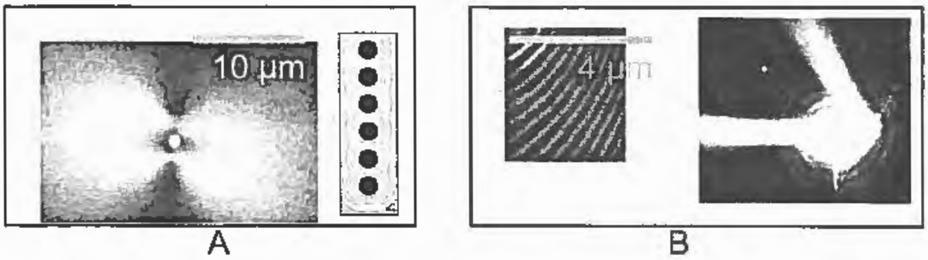

Figure 1. Localized surface plasmon dipole from a nanoparticle and a theoretical linear transport plasmonic chain of 25 nm particles (A). A surface plasmon polariton wave and an experimental plasmonic mirror constructed of five lines of 125 nm protrusions (B).

The need for precise control over aforementioned nanoscale structures had prevented the study and development of plasmonic circuits until methods for fabrication and arrangement of nanostructures made plasmonics plausible. Some of these methods include Ostwald ripening nanoparticle synthesis, nanoparticle digestive ripening,[10] electron beam lithography,[4] atomic force microscopy (AFM) manipulation,[4,11] and biomolecule.[12]

Equally important was the development of means to study and image surface plasmons in plasmonic components. The first, and currently most widely used instrument, is a scanning near-field optical microscope (SNOM or NSOM).[13] This instrument uses a pulled-fiber aperture probe to sense near-field electric field intensities very close to the metal surface. It has an advantage over scanning tunneling microscopy and AFM as it holds a dielectric fiber tip at a greater distance from the metal surface so as not to perturb the electromagnetic field being measured or induce a new field at the tip.[8] Finally, fluorescence microscopy can be used to probe surface plasmons by placing fluorescent molecules in a polymer matrix on the surface of thin metal films. Propagating SPPs on the metal surface excite the fluorophore and the fluorescent signal is subsequently imaged using a fluorescence microscope.[9]

Plasmonic components draw close analogy to standard optical components as manipulation of the electromagnetic energy is similar, however, the surface plasmons are held to two dimensions and are below the diffraction limit.[14] Transport via LSPs in linear chains of nanoparticles is still primarily theoretical with most interest displayed in calculation literature and experimental proof of concept using Yagi arrays.[4,6] However, directing SPPs on metal thin films has been realized for several plasmonic components including apertures, shutters, beam splitters, and reflective and focusing mirrors.[8,9,15,16]

Several components are necessary for implementation of plasmonics that have not yet been realized. These include couplers, waveguides, and switches. The creation of these components may quickly lead to experimental plasmonic circuits.[7]

Plasmonics will likely continue to advance over the next several decades, but several limitations currently prevent it from being commercially plausible. Current processors using electrical circuits require the transmission of an electrical signal on the order of tens of centimeters from generation to reading. Surface plasmons currently decay on the order of hundreds of microns[7] so a revolution of circuit architecture is necessary for plasmonics to be practical. However, as circuits and processors continue to shrink, plasmonics may become more readily useful. Also, although control over nanoscale structures has improved dramatically, there is still a need for better methods to create precisely monodisperse structures and perfectly controlled spacing to the resolution of angstroms. Finally, alignment of all components to complete a surface plasmon circuit must take place during circuit fabrication and cannot be accomplished post-fabrication as on an optical table.

References

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