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Abstract

The miniaturization of optical devices to spatial dimensions akin to their electronic device counterparts requires structures that guide electromagnetic energy with a lateral confinement below the diffraction limit of light. This cannot be achieved using conventional optical waveguides or photonic crystal defect waveguides. Thus, a size mismatch between electronic and optical integrated devices exists and needs to be overcome.

In this thesis, the possibility of employing plasmon-polariton excitations in “plasmon waveguides” consisting of closely spaced metal nanoclusters with a subwavelength cross section for the confinement and guiding of electromagnetic energy is examined both theoretically and experimentally. The feasibility of energy transport with mode sizes below the diffraction limit of visible light over distances of several hundred nanometers is demonstrated.

As a macroscopic analogue to nanoscale plasmon waveguides, the transport of electromagnetic energy in the microwave regime of the electromagnetic spectrum along structures consisting of closely spaced centimeter-scale metal rods is investigated. The dispersion relation for the propagation of electromagnetic waves is determined using full-field electrodynamic simulations, showing that information transport occurs at a group velocity of $0.65c$ for fabricated structures consisting of centimeter-scale copper rods excited at 8 GHz ($\lambda = 3.7$ cm). The electromagnetic energy is highly confined to the arrays, and the propagation loss in a straight array is about 6 dB/16 cm. Routing of energy around 90-degree corners is possible with a power loss of 3-4 dB, and tee structures for the splitting of the energy flow and for the fabrication of an all-optical modulator are investigated. Analogies to plasmon waveguides consisting of arrays of nanometer-size metal clusters are discussed.

The possibility of guiding electromagnetic energy at visible frequencies with mode sizes below the diffraction limit is analyzed using an analytical point-dipole model for energy transfer in ordered one-dimensional arrays of closely spaced metal nanoparticles. It is shown that such arrays can work as plasmon waveguides that guide electromagnetic energy on the nanoscale. Energy transport in these arrays occurs via near-field coupling between metal nanoparticles, which sets up plasmon modes. This coupling leads to coherent propagation of energy with group velocities exceeding the saturation velocity of electrons in semiconductor devices. The point-dipole model suggests the feasibility of complex guiding geometries such as 90-degree corners and tee structures for the routing of electromagnetic energy akin to the fabricated macroscopic guiding structures, and the possibility of an all-optical modulator operating below the diffraction limit is suggested.

The interparticle coupling in plasmon waveguides is examined using finite-difference time-domain (FDTD) simulations. Local excitations of plasmon waveguides show direct evidence for optical pulse propagation below the diffraction limit of light with group velocities up to 0.06*c* in plasmon waveguides consisting of arrays of spherical noble metal nanoparticles in air. The calculated dispersion relation and group velocities correlate well with predications from the simple point-dipole model. A change in particle shape to spheroidal particles shows up to a threefold increase in group velocity for structures that can be fabricated using electron beam lithography. Pulses with transverse polarization are shown to propagate with negative phase velocities antiparallel to the energy flow.

Plasmon waveguides consisting of spherical and spheroidal gold and silver nanoparticles were fabricated using electron beam lithography with lift-off on ITO coated quartz slides. Far-field polarization spectroscopy reveals the existence of longitudinal and transverse collective plasmon-polariton modes. Measurements of the polarization dependent extinction confirm that the collective modes arise from near-field optical interactions. The key parameters that govern the energy transport are determined for various interparticle spacings and particle chain lengths using measurements of the resonance frequencies of the collective plasmon modes. For spherical Au nanoparticles with a diameter of 50 nm and an interparticle spacing of 75 nm, the energy attenuation of the plasmon waveguide is 6 dB/30 nm. This loss can be reduced and the energy attenuation length conversely increased by approximately one order of magnitude by using spheroidal silver nanoparticles as building blocks of plasmon waveguides, which show an enhanced interparticle coupling and a decreased plasmon damping.

Near-field optical microscopy allows for the local optical analysis and excitation of plasmon waveguides. Using the tip of a near-field optical microscope as a local excitation source and fluorescent polystyrene nanospheres as detectors, experimental evidence for energy transport over a distance of about 0.5 μm is presented for plasmon waveguides consisting of silver rods with a 3:1 aspect ratio and a center-to-center spacing of 80 nm. Ways to further improve the efficiency of energy guiding in plasmon waveguides and possible applications are discussed.

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