Session 2P2
Surface Plasmon Photonics

Plasmons in nearly Touching Metallic Nanoparticles: Singular Response in the Limit of Touching Dimers

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We study the optical properties of pairs of spherical gold nanoparticles for light incident with its polarization parallel to the interparticle separation vector. Both the absorption of this system and the light scattering strength exhibit resonant features that shift in frequency when the separation between particles is varied. Distances close to the point of particle percolation are discussed in detail, where a rich structure of resonant features shows up. The evolution of overlapping spheres from the point where they touch to the point where they merge into a single sphere shows a resonant feature that shifts towards the far infrared region immediately in the limit when the spheres touch at a single point.

Temporal and Spectral Eependence of the Nonlinear Optical Properties of $Au: Al_2O_3$ and $Cu: Al_2O_3$ Composite Films

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Third order optical non-linearities in metal-dielectric nanocomposites have received considerable attention over the last years. These nanocomposites show large third order susceptibilities in the vicinity of the surface plasmon resonance with ultrafast build-up times. These characteristics make them promising for several applications in the field of information technologies like all-optical switching, signal regeneration or high speed demultiplexing [1]. Particularly, a very large third order nonlinear optical susceptibility has been recently reported for Cu nanocomposites near the percolation threshold that has been related to the appearance multiple particle interactions and giant local field enhancement effects [2].

The aim of this work is to investigate the spectral and temporal dependence of the third order non-linear response of Cu and Au nanocomposites embedded in Al_2O_3 with large metal volume fractions. Alternate pulsed laser deposition (PLD) is used to produce the samples. The nanocrystals are organized in layers that are separated by Al_2O_3. The total number of nanocrystal layers are of 10 and 5 respectively for the case of the $Cu: Al_2O_3$ and $Au: Al_2O_3$ samples while the spacing layers are 6 nm - thick and in both cases. In order to analyse the effect of the metal content and morphology in the non-linear optical properties of the nanocomposites, the dimensions and shape of the nanocrystals in each layer have been varied in different samples by increasing the metal content up to a limit close to the percolation threshold. The nonlinear optical properties of the films have been analyzed by degenerate four wave mixing and z-scan in the wavelength interval from 500 to 620 nm using laser pulses durations in the 100 fs - 10 ps interval.

For all the nanocomposites analysed (Cu and Au, and no matter the metal volume fraction), at wavelengths close to that of the surface plasmon resonance, the third order susceptibility values determined with laser pulses in the ps range are considerably higher (five to twenty times) than the ones obtained under fs laser pulses. The observed increase of the third order susceptibility for increasing pulse durations is bigger in the Cu than in Au nanocomposites. In both cases the third order susceptibility value observed saturates for pulse durations around 5 ps. These results are discussed in terms of the different physical mechanisms contributing to the effective third order susceptibility of the nanocomposites, including the possible contribution associated to the ultrafast heating of the nanoparticles related to the temperature dependence of their dielectric function.

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Flasmon Spectroscopy of Metallic Nanoparticles Close to Dielectric Substrates. Analysis of Particle-substrate Interaction Effects

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Plasmon spectroscopy of metallic nanoparticles has been a very active field of research during the last decade [1]. The excitation of lacalized plasmons, or plasmon resonances, in small metallic particles generates strong local electric fields very close to the particle surface. This enhancement of the electric field finds many applications that have generated new technologies in the nanoscopic world [1].

It is well known that the spectrum of plasmon resonances depends on the size and shape of the individual particles and also on the particle-particle interaction when the particle density is high and multiple scattering is important. This interaction modifies the spectrum in such a way that dipolar resonances shift (normally th the red) and other multipolar resonances appear [2, 3]. Usually, in experimental works with nanoparticles, these are grown inside a dielectric high-refractive-index matrix ($GaAs$, TiO_2, *a-Si*, *etc.*) in order to shift the resonance to the visible part of the spectrum [4, 5]. This matrix is ,in turn, located on a flat substrate, which normally is dielectric. In these works, particle shape and size, and particle-particle interaction are considered in order to account for the structure of the resonance (either, peak position or shape). Because of the presence of the substrate, particle-substrate interaction is another source of modification of the spectrum of the plasmon resonance, which can contribute to the shift of the dipolar component and also to the appearance of new resonances of higher orders, but it has not been considered so far.

In this research, we present a systematic numerical study of the scattering crosssection of a small metallic particle (Ag) immersed in a dielectric medium of refractive index n and located at a given distance above flat, dielectric substrate of refractive index n' ($> n$, $< n$). The geometry is restricted to the 1D case, which has been shown to be successful in dealing with this kind of electromagnetic problem [2]. The study is made as a function of both the distance to the substrate and the angle of incidence, the latter case to analyze the effect of the component of the incident electric field when it is parallel/perpendicular to the substrate. The numerical work has been performed by using exact numerical techniques based on the application of the Extinction Theorem of the Physical Optics [6], where the authors have previously studied scattering for both far and near field approximations [7, 8].

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Metallic Photonic Band Gap Structures for Laser Applications

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We report on a two dimensional plasmonic crystal laser structure that utilizes a thin Ag film for the generation of long range surface plasmons (LRSPs) and a layer of the organic semiconductor tri(8-hydroxyquinoline) aluminum (Alq3) doped with the laser dye 4-dicyanmethylene-2-methyl-6-(p-dimethylaminostyryl)-4H-pyran (DCM) as active medium. The dispersion diagram of this structure exhibits a plasmonic bandgap in the dye emission wavelength range. At the flat bandedge, the groupe velocity tends to zero, so that the density of surface plasmon modes is high. This yields a lasing action. However, the device suffers from the energy dissipation (metal absorption, unwanted radiation, etc.). We suggest few ways to minimize the effect of this problem. First, we propose the use of LRSPs characterized by a low loss coefficient. To this end, we investigate theoretically and experimentally the best conditions for the excitation of these modes. A strong emission is observed compared to that from a planar structure. These modes provide a high performance when the dye thickness is about 100 nm, a value consistent with the numerical findings. In addition, we demonstrate that the use of a spacer layer significantly increases the emission efficiency. We further suggest a new design for the laser structure for minimal radiation loss.

Surface-plasmon Polariton Scattering from a Finite Array of Nanodefects on Metal Surfaces

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We investigate theoretically and numerically the propagation and scattering of surface plasmon-polaritons (SPPs, evanescent waves, bounded to the interface, resulting from a blend of surface plasmons and photons) on surfaces structured with nano-defects. The formulations are based on the reduced Rayleigh equations obtained by imposing either the continuity conditions or the impedance boundary condition, rigorously accounting for all the scattering channels: SPP reflection and transmission, and radiative leakage. The scattering of SPP (both CW and pulsed excitation) in the visible and near IR by single (nano/micro)-defects [1, 2] and finite arrays of nano-defects [3] on an otherwise planar metal interface is studied; both are specially relevant in micro/nano-Optics of SPPs.

In particular, we analyze the range of parameters (defect size and number) for which high SPP reflection efficiency (low radiative losses and negligible SPP transmission) is achieved within a SPP band gap [3, 4], neglecting ohmic losses (justified for array lengths significantly shorter than the SPP inelastic length): Smaller defects play better as SPP mirrors (e.g., efficiency above 90% for Gaussian ridges/grooves with sub-30 nm height and half-width) than larger defects, since the latter yield significant radiative losses [3]. The impact of absorption in real metals on the efficiencies is discussed. Finally, the existence of localized states within the gap (of interest in resonant scattering or filtering) is studied upon introducing vacant sites, anomalous defects, etc.).

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How Light Emerges from an Illuminated Finite Array of Subwavelength Holes

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The extraordinary optical transmission (EOT) through periodic arrays has been extensively studied both experimental and theoretically since its discovery. However, to the best of our knowledge, all theoretical studies have concentrated on the case of an infinite array. By combining experiment and theory, we have analyzed the influence of the inherent finite size of the arrays. We find an unexpected spatial distribution of transmitted light which is both strongly anisotropic and extremely sensitive to the angle of incidence of the impinging light. This behaviour is explained by a simple model that takes into account the edges of the array and its effect on the emission pattern.

Experimental Realization of a Low Profile Metallic Bull's-Eye Antenna

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The very promising results, reported at optical wavelengths, of enhanced transmission phenomena through subwavelength apertures in corrugated metallic films and in hole arrays have stimulated the interest in this emergent research topic [1, 2]. For the case of optical wavelengths, one-dimensional arrays of very narrow slits have been theoretically analyzed and two types of transmission resonances were predicted [3, 4], coupled surface plasmon polariton (SPP) resonances and slit waveguide modes. Corrugated planes are well known for antenna engineers, but it has been recently demonstrated that the enhanced optical transmission phenomenon can be fully described by means of the excitation of a leaky mode, being in this case a leaky plasmon mode [5, 6]. This leaky mode enhances the aperture field at the entrance face, and also creates a narrow-beam pattern at the output region. By using reciprocity principle, it is shown that the two enhancement effects are equal. A microwave scaled version of these experiments can drive to new potential applications. In this work, a further step of these concepts that opens potential applications for very low profile feeder antennas is presented. Simulation as well as experimental results of a low profile metallic Bull's-Eye antenna are shown envisaging their potential application in communication systems. These structures can be considered as a kind of metamaterial where enhanced transmission and beaming is possible.

Transmission of Light through a Thin Metal Film with Periodically and Randomly Corrugated Surfaces

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We calculate the transmission of p- and s-polarized light, incident normally from vacuum, through a thin metal film deposited on a semi-infinite dielectric substrate. The vacuum-metal and metaldielectric interfaces are one-dimensional rough interfaces defined by $x_3 = -\zeta(x_1)$ and $x_3 = -H + \zeta(x_1)$, respectively, where the function $\zeta(x_1)$ has the form $\zeta(x_1) = d \sum_{n=-\infty}^{\infty} \exp[-(x_1 - nb - d_n b)^2/a^2]$, with $0 \leq d \leq H/2$. In this expression the $\{d_n\}$ are independent, identically distributed random deviates drawn from a uniform distribution. By means of a rigorous numerical approach the transmissivity of a single realization of the film is calculated as a function of the wavelength of the incident light, the amplitude d, and the width of the distribution from which the $\{d_n\}$ are drawn. Results for silver and gold films show that in comparison with the transmissivity of a film with planar surfaces ($d = 0$), the transmissivity is strongly enhanced in the case of a film with a periodically modulated thickness ($d_n \equiv 0$) for light of both p and s polarization even for moderate values of $d\,(= 0.2\,\mathrm{H})$. In the case of p polarization the transmissivity is further enhanced at the wavelengths of the surface plasmon polaritons supported by the scattering system. The enhancement of the transmissivity for both polarizations of the incident light is further increased as the amplitude d is increased up to $d = 0.4\,\mathrm{H}$. In the presence of nonzero randomness in the function $\zeta(x_1)$ the enhancement of the transmissivity in both polarizations is decreased for a given value of d from its value in the absence of the randomness, but a significant enhancement remains even when d_n is allowed to take values in the interval $(-0.2, 0.2)$. Thus, periodicity is sufficient to produce a significantly enhanced transmissivity, but it is not necessary.

Terahertz Surface-plasmon Polariton Scattering from Semiconductor Groove Arrays: Gap Formation and Switching

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We present experimental and theoretical results of terahertz surface plasmon polaritons (SPPs) propagating on gratings structured on semiconductor surfaces. Single-cycle pulses of terahertz radiation, focused on a gap formed by a razor blade closed to the interface, are used to excite SPPs in a broad frequency range. Time-domain measurements are performed by out-coupling the transmitted SPPs to radiated waves in a similar manner. A theoretical framework is presented that allows us to investigate the scattering of terahertz SPPs by arrays of sub-wavelength defects on semiconductors. The formulation is based on the reduced Rayleigh equation resulting upon imposing an impedance boundary condition. The efficient SPP scattering on the semiconductor periodic structure introduces significant dispersion and modifies the SPP propagation, leading to a rich phenomenology.

A stop gap, or a frequency range where SPPs are Bragg reflected, is observed on doped-Si surfaces. This gap depends strongly on the Si doping density and type. The resonant scattering at the edge of the gap reduces the group velocity by more than a factor of 2. The measurements show a good agreement with our numerical calculations [1].

Based on approximate estimations of the SPP gap broadening with temperature in the case of indium antimonide samples with rectangular grooves, numerical calculations are carried out to determine the spectral dependence of all the SPP scattering channels (reflection, transmission, and radiation) in the immediate vicinity of that gap. The thermally-induced SPP switching nearby the lower SPP band edge is investigated as a function of groove parameters (size and number), providing the most suitable configurations. Near-field intensity maps are presented that shed light onto the SPP scattering and switching physical mechanisms [2].

Our experimental results demonstrate indeed SPP switching for deep grooves. Since the above approximation is no longer valid for such groove depth, we make use instead of the formally exact Green's theorem surface integral equations to calculate the spectral dependence of the SPP transmission at different temperatures. Comparisons with experimental results yield good agreement [3].

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Surface Modes in Structured Metal Surfaces

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Surface-bound modes in metamaterials forged by drilling periodic hole arrays in perfect-conductor surfaces will be explored by means of both analytical techniques and numerical solution of Maxwell's equations. It will be shown that these metamaterials cannot be described in general by local, frequency-dependent permittivities and permeabilities for small periods compared to the wavelength, except in certain limiting cases. New related metamaterials are shown to exhibit optical properties that are elucidated in the light of our simple analytical approach.

Refraction of Surface Polaritons by a Surface Lens

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The scattering of surface plasmon polaritons by spatially localized surface defects has been studied both theoretically [1, 2] and experimentally [3]. Such scattering processes lead not only to a reflected surface plasmon polariton but also to radiation of electromagnetic waves into the vacuum above the metal surface on which the surface plasmon polariton propagates. When a surface plasmon polariton propagating along a metal surface impinges at oblique incidence on an extended linear surface defect such as a linear groove or a ridge on an otherwise planar surface, the translational invariance along the surface structure imposes a conservation law on the tangential components of the wave vectors of all waves excited by the interaction of the surface plasmon polariton with the structure, namely the reflected and transmitted surface plasmon polaritons as well as the radiated bulk waves. This is Snells law for surface plasmon polaritons. When the surface defect is formed from a different material, e.g., a dielectric film, so that in the region of the defect the surface plasmon polariton has a different wavenumber, the surface polariton is refracted at the boundary of the defect. In the present work we consider the transformation of surface plasmon polaritons at surface structures that are formed by a film on a planar (or corrugated) metal surface. In particular we are interested in the case where the boundary between the clean metal surface and the film is a parabola, for which the surface profile function is given by $\zeta(x_1, x_2) = d\theta(x_1 - ax_2^2)\theta(x_1)$, where $\theta(z)$ is the Heaviside unit step function, and d is the thickness of the film, and the case where the film has an elliptic shape for which $\zeta(x_1, x_2) = d\theta(1 - (x_1/a)^2 - (x_2/b)^2)$. The refraction of surface polaritons at the boundary of such structures on a metal surface leads to a focusing of the transmitted surface waves. The reduced Rayleigh equations for a vacuum/film/metal system with two two-dimensional rough interfaces are derived and solved numerically. The parameters of surface defects allowing an efficient focusing of surface plasmon polaritons are determined.

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