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Anomalous Electromagnetic Response of Composite Nanoparticle

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ABSTRACT We have analysed the anomalous electromagnetic response of composite nanoparticle formed by two conjoined half cylinders of arbitrary complex permittivity and radius. This geometry has been proposed in the special configuration to from a resonant optical nano circuit and attempts to analytically solved its scattering properties using mode matching analysis, integral transformation and coordinate mapping have led to non physical solutions and strong numerical instabilities. We have shown that these challenges are associated with counterintuitive resonant phenomena which leaded to continuous frequency range over which distributed Plasmon resonances may support unbounded values of absorption or gain efficiency i.e. finite absorption or grain even in the limit of infinitesimally small material loss/gain. We solved the complete scattering problem associated with this geometry derived closed form expressions for the induced fields inside and outside this composite particle. This solution provides valuable physical insights into the complex wave interaction of this particle over a broad range of frequencies which provide exciting possibilities for energy concentration, harvesting and spasars. This absorption paradox has been shown to be associated with the singularities in the geometry and the adiabatic focusing of broad band surface plasmons supported at the corners. A close form solution was derived for the scattering and absorption properties of the composite nanostructure and simple conditions on the material permittivity have been derived to control the position of the absorption band.

KEYWORDS Anomalous, nanoparticle, permittivity, scattering, Plasmon, resonance, concentration.

INTRODUCTION

Kelly et al. [1] and prodon et al. [2] analyzed different configurations from simple nanospheres and core shell structures to more complicated shapes, like crescent shaped cylinders. Lukyanchuk et al. [3] and Argyropoulos et al. [4] showed that if simple structures are known to support strong, sharp Plasmon resonances, more complicated shapes provide more complex scattering responses, such as Fano and electromagnetically induced transparency resonances or broad band operation. Chu [5] studied that many of the exotic properties of these geometries often appear to contradict well established physical limitations of resonant subwavelength systems and the underlying physics is often difficultly captured because of the complex interaction between multiple resonances and plasmonic effects. A Key parameter is the fabrication limitation dictated by technological challenges. Particles with exotic shapes and very fine structures showing electromagnetic properties. Sun et al. [6] and Bastys et al. [7] studied that optical properties of nanoparticles has led to the many counterintutitive scattering features in plasmonic nanostructures. Barnes et al. [8], Maier [9] and Polman [10] showed that due to negative real part of permittivity, these particles support surface Plasmon resonances at the nanoscale that have been proposed for many exciting applications, including field concentration, sensing, nanolasing and optical guiding.

METHOD

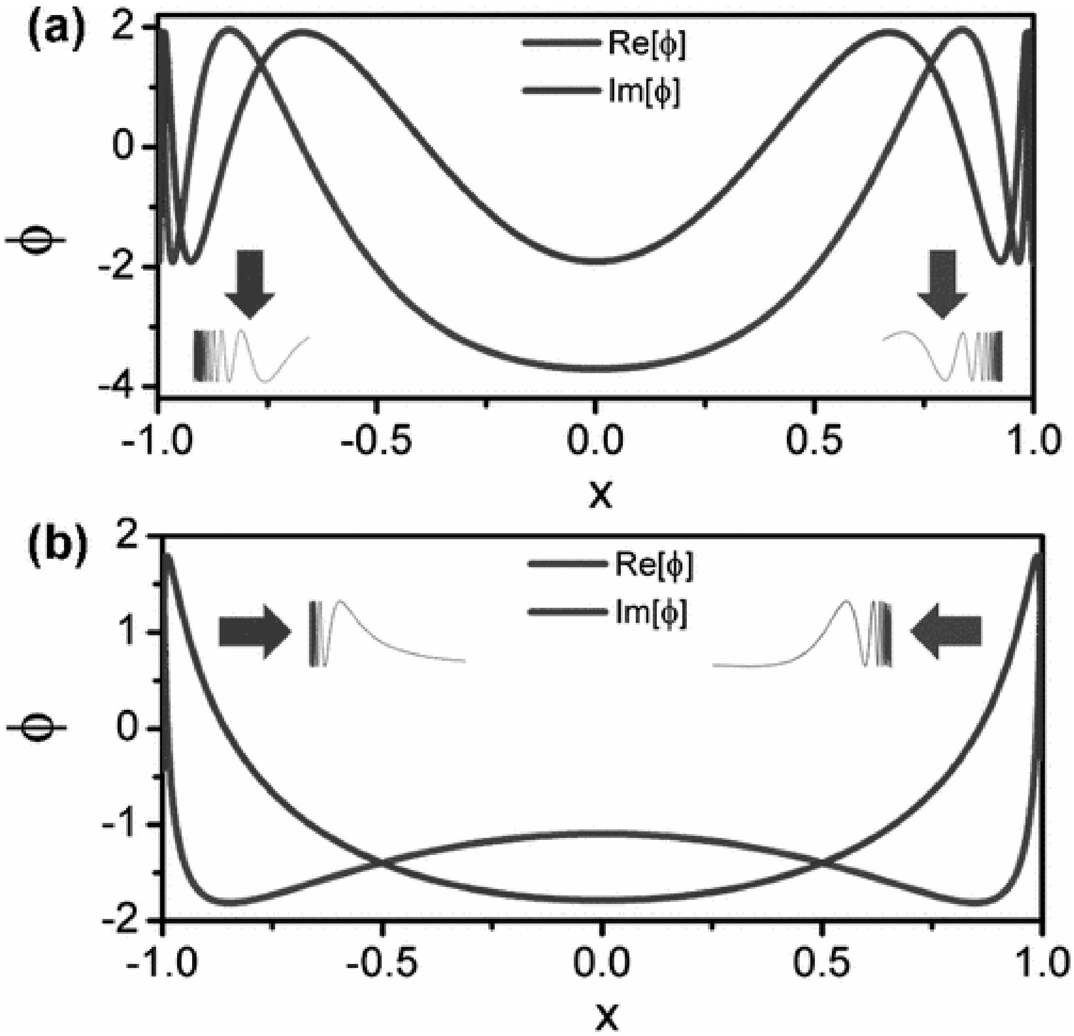
We solved the scattering problem in quasistatic limit under the assumption $a << \lambda_o$. An incident monochromatic wave with electric field E_0 illuminates the nanostructure under and e^{jwt} time convention and the permittivities of the two half cylinders can take arbitrary complex values, whose imaginary parts correspond to material loss or gain depending on their negative or positive sign due to symmetries and linearity the problem may be split into two orthogonal excitations with respect to the common diameter of the structure. By using separation variables in the two dimensional bipolar co-ordinate system the potential distribution in each material may be written as

$$\phi_i(u,v) = \int_o^\infty U(u)\left[C_{i1}(\lambda)\cosh(\lambda v) + C_{i2}(\lambda)\sinh(\lambda v)\right] d\lambda$$

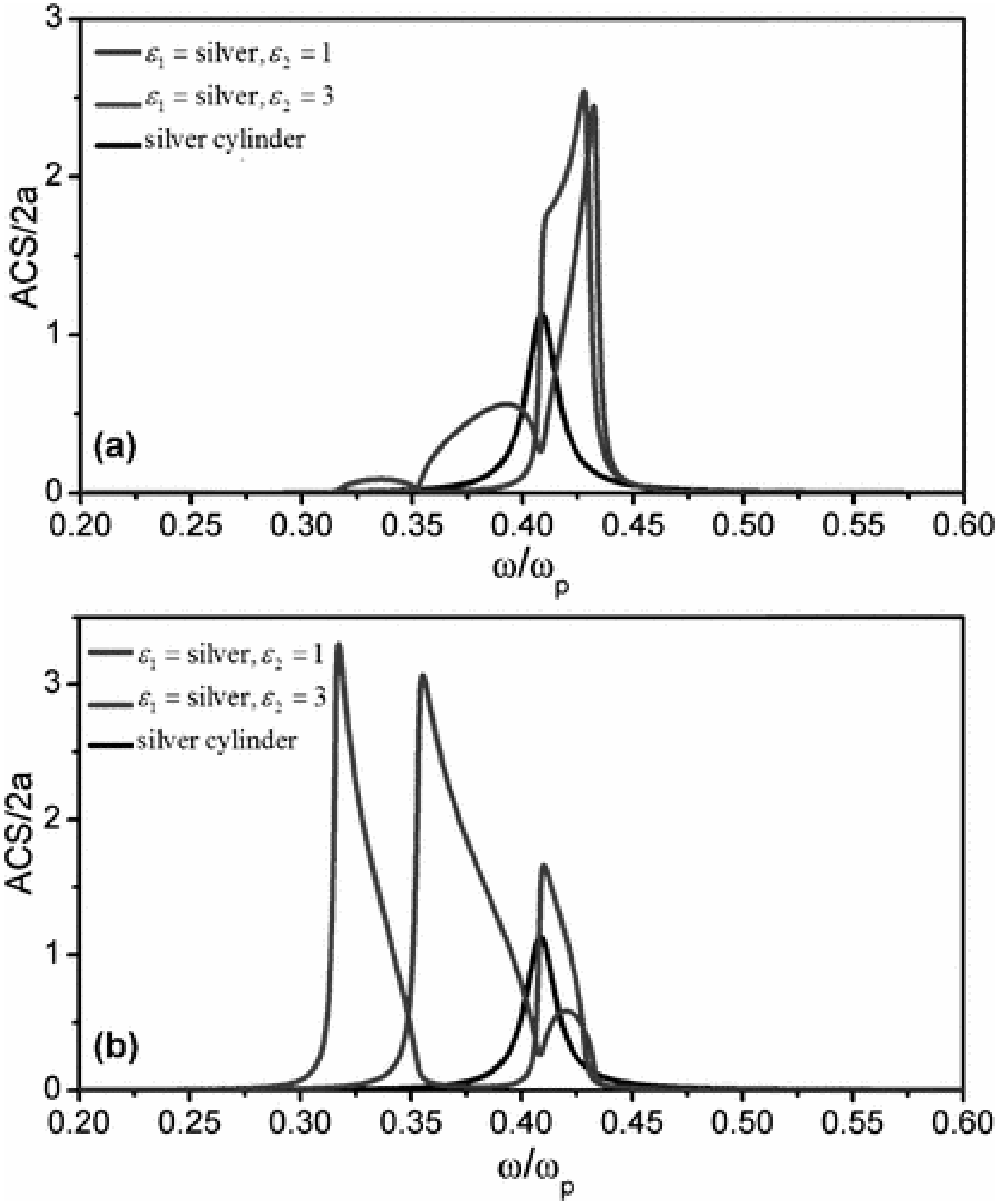
in which the subscript 1,2,0 refers to upper, lower and outer regions, λ is the continuous eigen value, U(u) is either $\cos(\lambda u)$ or $\sin(\lambda u)$ for longitudinal and transverse polarizations and $-\infty < u < \infty$ and $-\pi < v \le \pi$ are bipolar coordinate variables. The unknown coefficients $C_{ij}(\lambda)$ may be found by applying suitable boundary conditions at the various boundaries to calculate the general form of potential distribution in all space.

RESULTS AND DISCUSSION

Graph (1) shows the potential variation along the common diameter of the particle different values of permittivities of the particle different values of permittivities as $\varepsilon_1 = -2, \varepsilon = 1$. The different behavior between $\varepsilon_1 = -1.1$ and $\varepsilon_1 = -2$ have been shown. For values of ξ_1 near -1 the frequency of spatial oscillations is much larger compared to $\varepsilon_1 = -2$, resulting in oscillations extended farther from the corners. For these situations, the field enhancement may be extended more broadly all over the particle; with interesting possibilities to more effectively enhance optical nonlinearities. These distributed resonances and adiabatic focusing have direct analogies with the resonant distribution for crescent shaped and touching plasmonic cylinders but it is obtained in an arguably simpler geometry over a flat surface and controllable frequency bands. Graph (2) shows the absorption cross section normalized to the physical width of the particle for composite cylinders with 2a=40nm compared to the case of a homogeneous cylinder of same size. In this case in order to include also frequency dispersion and realistic material absorption, the upper half cylinder is chosen to be silver with $\varepsilon_r = \varepsilon_\infty - \omega_p^2 / \omega(\omega - jT)$, $\varepsilon_\infty = 5$ $\omega_p = 2\pi \times 175$ THz and $T = 2\pi \times 4.35$ THz. We have compared the case of a silver hemi-cylinder $\varepsilon_2 = 1$, the case $\varepsilon_2 = 3$ which have different resonant bands. The results confirm that absorption /gain may be largely enhanced over a continuous and controllable frequency band, significantly broadening the range and level of absorption/ gain compared to a full circular rod of the same material. For a half cylinder, the absorption is drastically enhanced in frequency bands corresponding to the resonance region $-3 < \varepsilon_1 < -1$ and $-1 < \varepsilon_1 < -\frac{1}{3}$ and is negligible at other frequencies. We observed that this particle shows a lower amount of absorption around the frequency for which $\xi_1 = -1$ at which we have the highest absorption in full cylinder case. Counterintunitively this absorption band does not rely on material losses and is larger in the limit of zero losses.



Graph 1: (a) Real and imaginary parts of the normalized potential distribution for a half-cylinder with ε_1=−1.1 under longitudinal excitation along the x axis. (b) Same distributions when ε_1=−2 .



Graph 2: Normalized absorption cross-section for (a) longitudinal and (b) transverse excitation of a composite nanoparticle with upper half-cylinder made of silver and different values of ε_2.

CONCLUSION

We have studied the anomalous electromagnetic response of simple composite nanoparticle formed by two conjoined half cylinders of arbitrary complex permittivity. We found that over a continuous frequency range the composite nanostructure shows finite amount of absorption/amplification even in the limit of infinitesimally small intrinsic material loss/ gain. It was found that in the ideal case of perfect corners this geometry provided broad band light absorption or amplification in the limit of negligible material loss or gain. A closed form solution was derived for the scattering and absorption properties of the composite nanostructure. Simple conditions on the material permittivities have been derived to control the position of the absorption band. This solution provided valuable physical insights into complex wave interaction of this particle over a broad range of frequencies. The obtained results were compared to previously obtain theoretical and experimental result and were found in good agreement.

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