Collection and Concentration of Light by Touching Spheres: A Transformation Optics Approach

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Abstract

A general three-dimensional transformation optics approach is presented that yields analytical expressions for the relevant electromagnetic magnitudes in plasmonic phenomena at singular geometries. This powerful theoretical tool reveals the broadband response and superfocusing properties of touching metal nanospheres and provides an elegant physical description of the prominent field enhancement that takes place at the point of contact between a spherical nanoparticle and a flat metallic surface.

1. Introduction

During the last decade, transformation optics [1] has become the theoretical framework driving the development of metamaterials science. This powerful tool, which exploits the invariance of Maxwell's equations under coordinate transformations, provides the link between a desired electromagnetic effect and the material properties required for its occurrence [2]. In this context, it establishes how the electromagnetic constitutive relations must be modified within a metamaterial structure in order to achieve a given optical response. Similar ideas have been also transferred to plasmonics, and the routing of surface plasmon polaritons through transformation optics has been reported lately [3,4].

In the last year, several theoretical works have recovered the original purpose of transformation optics, first thought as a strategy to ease the solution of Maxwell's equations, by applying it to the analytical treatment of the interaction of light with 2D metallic nanostructures. The idea is as follows: using a spatial transformation, plasmonic structures with geometric singularities can be mapped into more manageable geometries, where electromagnetic fields can be calculated analytically. By transforming back to the original frame, the optical properties of the initial system are known, and simple expressions for magnitudes such as the cross section or the near field enhancement can be obtained. Apart from the deep physical insight that this method offers, the analytical treatment of singular 2D geometries such as crescents [5], wedges [6], or touching nanowires [7], has also opened the way to the solution of one of the paradigms of modern photonics: the design of nanometric devices able to collect and concentrate light efficiently within a wide spectral range.

In this work [8], we move a step forward in this direction by developing an elegant 3D transformation optics approach that provides us with a complete physical description of the interaction of light with touching nanospheres. This methodology allows us to demonstrate the efficient light harvesting capabilities of touching nanoparticle dimers as well as the remarkable field enhancement featured by a single nanosphere in contact with a flat metallic surface. Our approach yields simple analytical expressions for the relevant EM magnitudes in such geometries and evidences the fundamental role that surface plasmon modes play in the highly effective far-to-near field transfer of radiation that occurs in these singular nanoparticle configurations.

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2. Dimers of touching nanospheres

Fig. 1 plots the absorption cross section, σ_{abs}, normalized to the dimer volume for Ag twin spheres of different sizes calculated numerically (color dots). The analytical spectrum obtained from our Transformation Optics approach, which yields,

$$\sigma_{\text{abs}} = \frac{64\pi^2\omega}{3c}\text{Re}\{\alpha^2(\omega) - \alpha(\omega)\}, \quad (1)$$

with $\alpha(\omega) = \ln[(\epsilon(\omega) - 1)/(\epsilon(\omega) + 1)]$ is also shown in black solid line. The agreement between theory and simulations is remarkable for radii up to 35 nm, where the near-field approximation considered in the analytical formalism fails, and radiation losses become significant. Note that the comparison for small radii worsens at high frequencies, as metal absorption prevents electromagnetic fields from reaching the touching point, where our theoretical results are most accurate. Fig. 1 indicates that σ_{abs} for small dimmers is of the order of the physical size even at frequencies well below the single sphere resonance (black dots). This demonstrates that touching dimers interact strongly with radiation over the whole optical spectrum, and that their cross section presents a much smoother dependence on frequency than isolated particles.

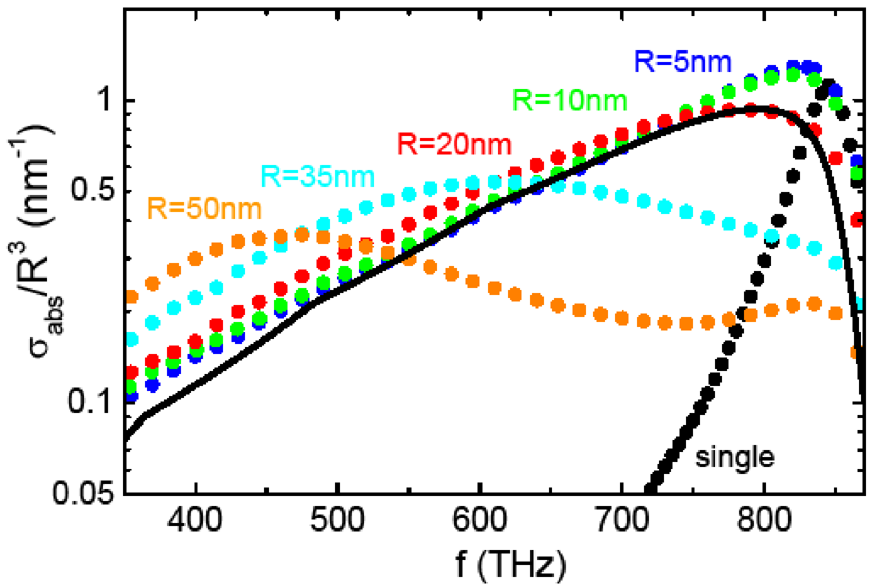

Fig. 1: Numerical absorption cross section for twin Ag touching spheres of different radii, and a single 5 nm radius sphere (dots). Black solid line plots the cross section obtained from Eq. (1).

3. Nanosphere on top of a metal surface

Our method also allows us to explore another interesting geometry, a single sphere on top of a metal surface (see inset of Fig. 2). This geometry has demonstrated promising field enhancement capabilities in recent experimental reports [9]. Fig. 2 displays the comparison between the transformation optics prediction (black line), and full electrodynamic simulations for different particle radii (small color dots) at 500 THz. It demonstrates the validity of our approach, and shows that notable amplitude enhancements, of the order of 10^4, occur even for particle diameters comparable to the incoming wavelength.

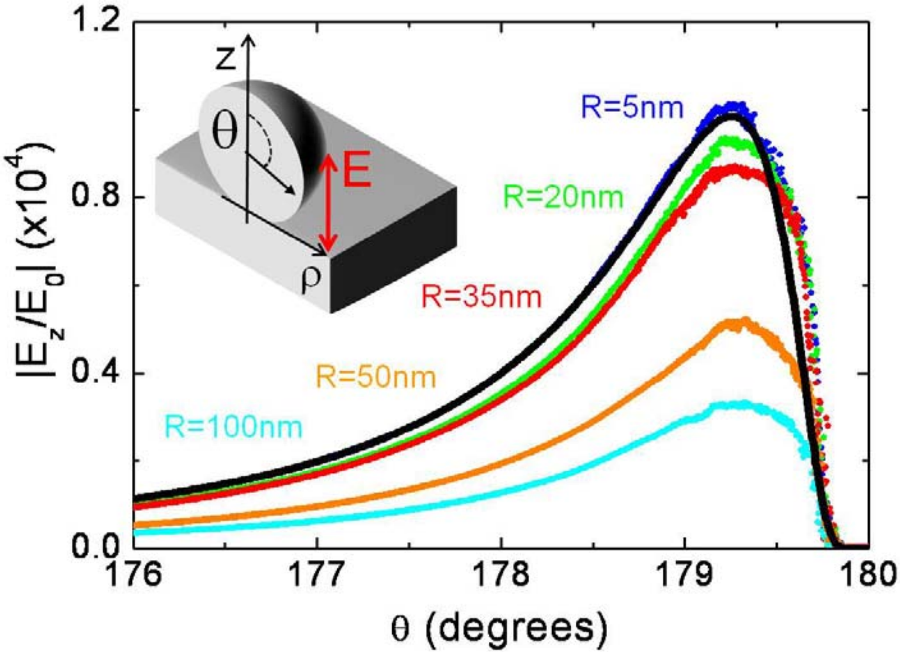

Fig. 2: Field enhancement at the point of contact between a silver surface and nanoparticles of different radii at 500 THz. Black line plots the analytical result and small colour or shaded dots correspond to simulations.

4. Conclusion

In conclusion, we have shown that three-dimensional transformation optics can be used to study plasmonic effects in geometric singularities. We have demonstrated the highly efficient ability of nanosphere dimers to collect and concentrate broadband radiation at their touching point. We have also evidenced the mechanisms governing the prominent field enhancement that takes place at the point of contact between a spherical nanoparticle and a metal surface. Importantly, although we have focused on touching geometries, our approach can be extended to other configurations, such as overlapping nanoparticles, via the exploitation of more complex transformations. Apart from the profound physical insight that our theoretical results provide on electromagnetic phenomena at singular metal nanostructures, we expect that our analytical framework will make possible a deep exploration of nonlinear and nonlocal effects in such systems

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