A Network Formulation for Characterization of Plasmonic Interactions in a Semiconductor Nanodimer

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***Abstract*— An effective-field approach is employed to arrive at the total dipole moment induced on a nanodimer by a terahertz electric field. The implemented formulation is aided by the use of networks synthesized from the polarizability of the particles, enabling close form expressions to be obtained. Salient features such as field enhancement and spectral shift in the surface plasmon resonance frequency exhibited by a nanodimer comprise of conductive particles are revealed by the calculated total dipole moment. The method can be directly extended to gain insight to polarization interactions in larger clusters with only a moderate increase in computation effort.**

I. INTRODUCTION

SEMICONDUCTOR nanoparticles can be expected to have good prospects for sensing and device applications in the terahertz frequency range [1], as their bulk plasma frequency can be tuned by doping or carrier injection over a substantial range. With the advent of techniques in material synthesis and microfabrication, considerable attention has recently been paid to the characterization of elementary aggregates of metal particles such as the nanodimer [2]. This is an important step in accumulating the needed knowledge base on the building blocks of circuitry employing nanostructures.

To account for the collective effects of the polarization in an aggregate of polarizable entities, the interactions among the particles need to be taken into consideration. Solving for the coupled electric field in a collection of particles with the charge dynamics accounted for is a computationally intense process. To gain insight to the interactions of polarizations and to develop tractable models to characterize clusters of various configurations, simplifying models that captures the essential mechanisms governing the interactions that are amenable to close form mathematical expressions can have a role in both the analysis and design of functional clusters.

II. EFFECTIVE-FIELD FORMULATION

In this investigation, an effective-field formulation is introduced to account for the polarization effect of a member particle on its neighbors so that the local field can be estimated in the cluster. The objective is to arrive at a close-form expression for the collective dipole moment of a cluster of particles using the polarizability of a single particle as the intrinsic response function. Assuming the polarizability of an isolated particle is already known as $\alpha(\omega)$, the polarization of a particle in the dimer subjected to an linearly polarized applied electric field can be written in terms of an effective value of the total, which is taken to be at the center location of the particle being considered, so that.

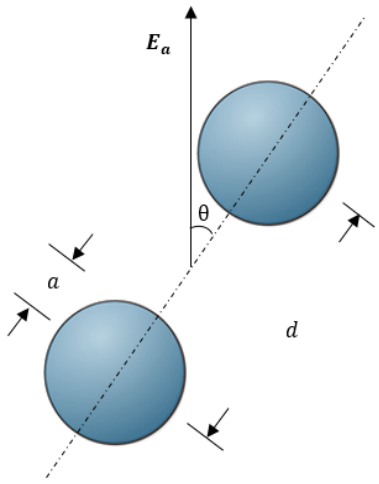

Fig. 1. A nanodimer in a linearly polarized electric field

$$\boldsymbol{p}_i = \alpha(\omega)\boldsymbol{E}_t(\boldsymbol{r}_i) \tag{1}$$

i = 1, 2 for the case of a dimer, as shown in Figure 1. And ri is the position vector for the center of particle i. The induced dipole moment of a particle in the dimer can be written as

$$\boldsymbol{p}_i = \alpha(\omega)\boldsymbol{E}_a + \alpha(\omega)\boldsymbol{p}_j\boldsymbol{g}_{dip}(\boldsymbol{r}_i - \boldsymbol{r}_j) \tag{2}$$

where $\boldsymbol{p}_i$ is the dipole moment of particle i and $\boldsymbol{g}_{dip}$(r) is the electric field due to a dipole of unit dipole moment. For a known α(ω), the dipole moment of each particle can be solved for and the total dipole moment of the dimer can readily be obtained.

The calculation is facilitated by analytic expressions for $\alpha(\omega)$, which can be obtained by considering an equivalent circuit synthesized from the numerical results of electromagnetic simulation for an isolated nanoparticle [3].

In the equivalent circuit of Figure 2, the two sub-circuits enclosed by the dotted lines represent the intrinsic polarizability of an individual particle. When they are coupled in a dimer configuration, the coupling action is accounted for by the two controlled sources. The transimpedance of the controlled source is given by the coupling coefficient relating the current moment in one particle to the local electric field of the other. From the generalized driving-point admittance of the equivalent circuit, the polarizability of the dimer can be obtained as

$$\alpha_m(\omega) = \left(\frac{Y}{j\omega}\right) \tag{3}$$

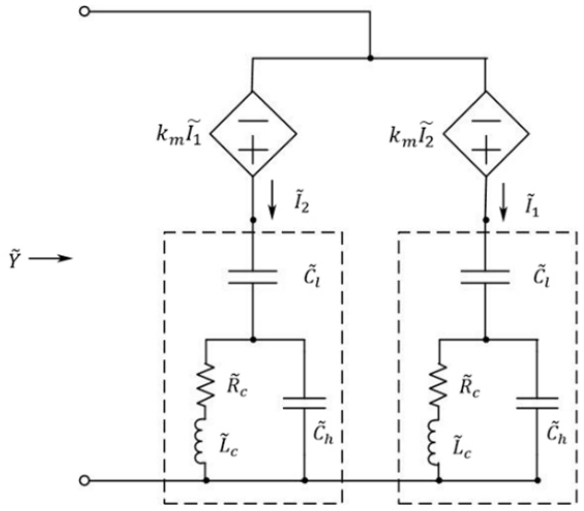

Fig. 2. Equivalent circuit of the nanodimer excited in one of the normal modes

which can readily be inserted into (1) to obtained the total dipole moment ***p*** of the dimer under the action of an applied electric field. The dipole moment of a semiconductor nanodimer with radius of the particle $a = 50\ nm$, gap between the particles = 50 *nm,* doping level $Ne = 10^{19}\ cm^{-3}$, relative permittivity $\varepsilon_r = 10$, electron effective mass $m^* = 0.25m_o$ and momentum relaxation time $\tau_n = 2\times10^{-13}\ s$ is shown in Fig. 3.

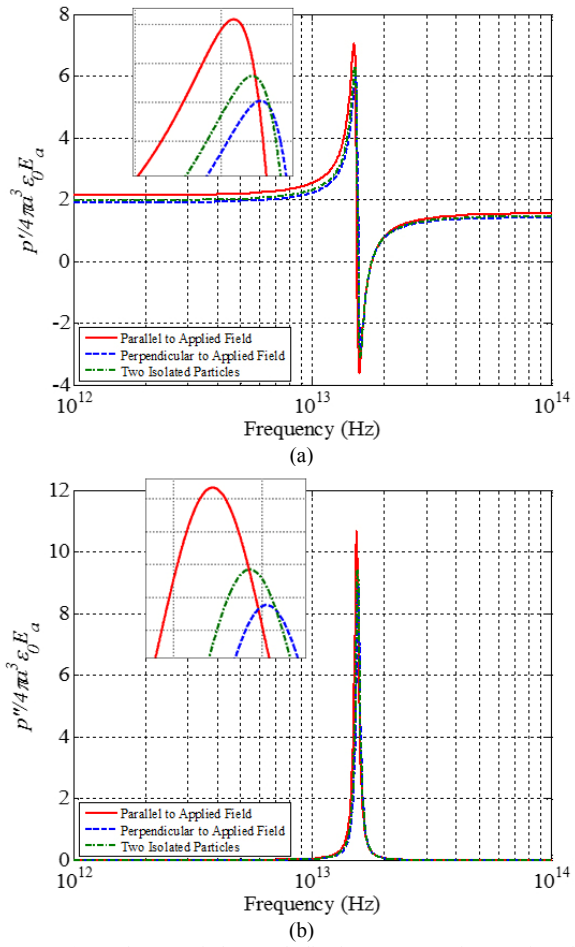

Fig. 3. (a) Real part of the total dipole moment of a semiconductor nanodimer, (b) imaginary part.

It can be observed from the figure that the dipole moment is enhanced and the plasmon resonance is red-shifted when the axis of the dimer is parallel to the applied field. The opposite is observed when the axis of the dimer is perpendicular to the applied field.

III. Discussion

With the provision from the single-particle polarizability, the collective dipole moment of a nanocluster comprised of identical particles can readily obtained using an effective-field approach implemented with a network formulation. Field enhancement effect and spectral shift of the surface plasmon resonance are both qualitatively accounted for in the case of a semiconductor nanodimer. The formulation can readily be extended to more complex clusters, with the complexity in the computation effort increasing only in a linear manner. The accuracy of the predicted field enhancement and frequency shift is limited by the effective field approximation. Further refinement of the formulation can be made by incorporating more sophisticated equivalent circuits representing an individual particle under a non-uniform applied field.

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References

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