Journal of Quantitative Spectroscopy & Radiative Transfer 120 (2013) 70–80

Contents lists available at SciVerse ScienceDirect

Journal of Quantitative Spectroscopy & Radiative Transfer

journal homepage: www.elsevier.com/locate/jqsrt

Engineering the broadband spectrum of close-packed plasmonic honeycomb array surfaces

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ARTICLE INFO

Article history:
Received 12 September 2012
Received in revised form
17 January 2013
Accepted 20 January 2013
Available online 13 February 2013

Keywords:
Broadband
Spectroscopy
Plasmonics
Nanoantennas

ABSTRACT

Plasmonic nanostructures operating over a wide spectrum are promising candidates for broadband spectroscopic applications. While promising, spectral engineering of close-packed plasmonic honeycomb nanoantenna arrays is challenging due to the strong correlation between the particle geometry and hexagonal grid, particle coupling within unit cells, and interaction between neighboring unit cells. In this study, we demonstrate that the spectral distribution of large scale surfaces can be effectively tailored over a wideband spectral range using close-packed plasmonic honeycomb array surfaces. We discuss coupling-mechanisms responsible for the spectral response of honeycomb arrays and discuss the geometrical restrictions limiting the bandwidth of the spectral response. These limitations can be overcome with a more general honeycomb structure by introducing additional morphological parameters within the Wigner–Seitz unit cell. The proposed morphological parameters provide additional flexibility for manipulating the spectrum by relaxing geometrical restrictions due to a strong correlation between the unit-cell and nanoparticle morphology. Furthermore, we achieve spectral broadening by breaking the symmetry within a Wigner–Seitz unit cell on a hexagonal grid, rather than breaking the symmetry of the hexagonal grid itself via generalized honeycomb arrays. Additionally, we demonstrate the advantages of close-packed arrays in terms of spectral response and electric field enhancement over large surfaces. Finally, radiative far-field properties, absorptance, transmittance, and reflectance of honeycomb structures are investigated.

1. Introduction

Nanoparticles and artificial structures composed of a special arrangement of nanoparticles are one of the most fascinating fields for scientists and engineers due to their unique optical properties [1–3]. Among these nanosystems, plasmonic nanoparticles of different shapes have recently attracted significant interest due to the tunability of their resonances, their ability to manipulate light beyond the diffraction limit, and strong electromagnetic fields associated with their optical resonances [4–6]. The two dimensional surface arrangement of plasmonic structures [7] demonstrates many interesting optical properties such as extraordinary transmission through subwavelength hole arrays at optical wavelengths [8], localization of electromagnetic energy to subwavelength regions [9], electrically induced transparency at the optical regime [10,11] and negative refractive index metamaterials [12]. These exciting properties of plasmonic nanoparticles and the arrangement of nanoparticles for desired optical properties have opened up the fields of plasmonics [13–15] and optical metamaterials [12] in the quest for materials with improved optical functionality.

Optical nanoantennas [16–18] and radiative energy transfer at the nanoscale [19–23] have led to significant advances in nanotechnology. Recent advances in plasmonic

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0022-4073/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jqsrt.2013.01.026

and photovoltaic devices involving a wideband absorption spectrum, such as solar cells [24] and nonlinear process enhancement [25], have increased the research on broadband plasmonic structures [26–33].

To address the aforementioned need for a unidirectional wideband absorption and field enhancement spectrum over a large surface area, we proposed [29] a plasmonic honeycomb antenna array with broken symmetry. The honeycomb nanoantenna array, shown in Fig. 1, is based on a hexagonal grid with periodically arranged plasmonic antennas as Wigner–Seitz cell building blocks. This design offers advantages in terms of wideband spectral operation, unidirectional field patterns, and field enhancement over a large surface area. Due to the broken symmetry of the Wigner–Seitz cell, multiple resonances are supported by the plasmonic honeycomb antenna array over a broad spectrum [29]. The constructive interference of the vectoral superposition of the fields produced by the Wigner–Seitz unit cells provides the unidirectional feature of the wideband spectrum over the plasmonic antenna surface.

In our previous study [29], simple rod-like structures were utilized. As is well-known in the literature, particle shape plays an important role in spectrum engineering. Changing particle geometry in close-packed antenna arrays, however, has challenges. This challenge is due to the strong correlation of the particle shape and length with the repeating unit cell geometry. In other words, the morphology of the nanoantenna particles and array unit cells are strongly dependent on each other. As we will discuss in this article, the length of the particle cannot be arbitrarily changed and is limited by the geometric constraints on the unit cell geometry. This constraint limits the spectral tunability of close-packed arrays. In this study, we propose a generalized close-packed honeycomb array by introducing additional morphological parameters within the Wigner–Seitz unit cell. The generalized honeycomb plasmonic antenna array provides additional flexibility in the manipulation of the spectral response via these new morphological parameters by relaxing geometrical restrictions due to particle length and angles within the Wigner–Seitz unit cell.

Another contribution of this study is the suggestion of an alternative technique for breaking the symmetry of plasmonic honeycomb antenna arrays. In this study, we have demonstrated that spectral broadening can also achieved by breaking the symmetry within the Wigner–Seitz unit cell on a hexagonal grid, rather than breaking the symmetry of the hexagonal grid itself. Also in this study, the advantages of close-packing the antenna arrays are demonstrated in terms of spectral response, field enhancement, and absorption over a large surface area. In addition, we discuss the coupling mechanism of the plasmonic antenna array elements in forming the spectral features. Also in this study, radiative far-field properties such as absorptance, transmittance, and reflectance of honeycomb structures are investigated.

The paper is organized as follows. In Section 2, a summary of the solution technique is provided. In Section 3, the coupling mechanisms are discussed for the plasmonic honeycomb antenna arrays in forming the spectral features over a broad spectrum. Also in this section, we introduce geometrical restrictions on asymmetrical Wigner–Seitz unit cells. Then we clarify the spectral features of the honeycomb array in terms of couplings between the individual particles and discuss the limitations of geometrical restrictions on spectral response. In Section 4, we propose a more general family of honeycomb arrays by introducing additional parameters within the unit cell. In this section, spectral broadening is achieved by breaking the symmetry of the morphology within Wigner–Seitz unit cells where the hexagonal grid can be kept symmetric. By employing this type of symmetry breaking, geometrical restrictions which reduce the flexibility of spectral tailoring are relaxed. In Section 5, we demonstrate the advantages of close-packed arrays in terms of spectral response and field enhancement over large surfaces. In Section 6, we investigated the far-field radiative properties of honeycomb plasmonic nanoantenna array, such as absorptance, transmittance, and reflectance.

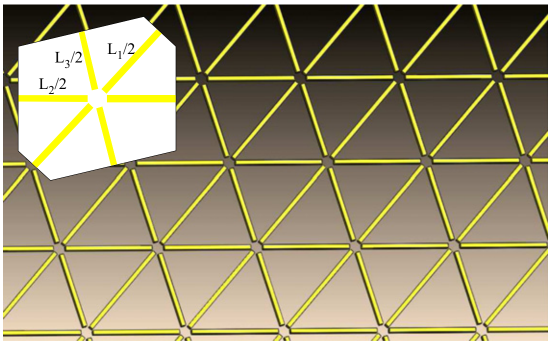

Fig. 1. A honeycomb array consisting of rod like particles and the corresponding unit cell (inset).

2. Methodology

In this study a 3-D frequency domain finite element method based on a full-wave solution of Maxwell's equations is used to obtain near field enhancement and far-field absorptance, transmittance, and reflectance of the honeycomb structures. The accuracy of the solution technique was previously validated by comparison with other solution techniques [34,35]. To calculate the scattered field $\vec{E}_s(\vec{r})$, the honeycomb structure is illuminated with a circularly polarized plane wave at the normal incidence to the plasmonic array surface to effectively excite all of the particles oriented in different directions. Once the scattered field is obtained, the total electric field $\vec{E}_t(\vec{r})$ is calculated as $\vec{E}_t(\vec{r}) = \vec{E}_i(\vec{r}) + \vec{E}_s(\vec{r})$ where $\vec{E}_i(\vec{r})$ is the incident plane wave. For the analysis of the nanoantenna array, periodic boundary conditions are used to reduce the computational time and memory demands. This boundary condition mimics the periodic nature of the nanoantenna array, by analyzing a single Wigner–Seitz unit cell, rather than by analyzing a layer containing large numbers of repeating antenna geometries. To account for the presence of neighboring unit cells, three periodic boundary conditions are defined on the three mutual, face-to-face lateral surfaces of the hexagonal shaped Wigner–Seitz unit cell. On the top