Optical Performance of Clusters of Plasmonic Nanoantennas: Periodic, Disordered and Aperiodic Arrays

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Abstract

The goal of this paper is to present a computational scheme to accurately and efficiently characterize the interactions between optical waves and clusters of metamaterials comprising of plasmonic nanorod antennas. The clusters studied herein are two-dimensional periodic arrays, disordered finite arrays, and Fibonacci quasi-lattices. To efficiently model the complex structure we take advantage of Characteristic Basis Function Method (CBFM) in conjunction with Macro Basis Functions. The proposed computational scheme achieves speed and memory performances that are considerably superior to that of the conventional approaches (orders of magnitude improvement). Novel physics are demonstrated.

1. Introduction

Metamaterials comprising of clusters of plasmonic nanorod antennas demonstrate wide range of applications in photonics, such as energy engineering in thin film solar cells [1, 2]. Two-dimensional Fibonacci quasi-lattice of plasmonic nanoantennas is an example of Deterministic Aperiodic (DA) arrays which have recently attracted a considerable interest due to their unique capability to robustly enhance and localize electromagnetic fields at multiple frequencies within engineered optical chips for nanoplasmonic applications [3]. Solving an array of plasmonic nanorods comprising of dispersive and negative-permittivity materials by using conventional EM simulation packages are often inaccurate or highly time- and memory-consuming because of the fine meshing due to the thin cross-section and that such large cluster of nanorods needs a lot of unknowns rendering the problem computationally intensive. The Characteristic Basis Function Method (CBFM) [4] has been found to be computationally efficient, and typically orders of magnitude faster than alternate approaches for analyzing array-type problems. The CBFM in conjunction with the concept of progressively expanding rings along with Parseval's theorem is used to derive closed-form expressions for the reflection and transmission coefficients for a periodic infinite array of plasmonic nanorod antennas illuminated by an obliquely incident plane wave. The effect of small random rotation around the centroid of the nanorods, an uncontrollable disorder, is studied. The formulation is also employed to investigate the electromagnetic response of the Fibonacci plasmonic quasi-lattice comprising of two different nanorods with two different lengths to provide multi/wide band characteristics.

2. Periodic and Non-Periodic Clusters of Nanoantennas

The unit cell of array structure is constructed from a plasmonic nanorod as shown in Fig. 1(a). It comprises silver with Drude material of $\varepsilon_r = \varepsilon_{r\infty} - f_p^2 / \left[f(f - jf_d) \right]$, where f_p and f_d are plasma and damping frequencies. To provide a fast and efficient analysis for array configuration one would need a sophisticated approach for nanorod modeling. By discretizing the polarized current using only a few piecewise sinusoidal Macro Basis Functions (MBFs), as depicted in Fig. 1(b), and by employing Galerkin testing on the surface of the nanorod, one can derive an accurate, fast and singularity free computational paradigm [5]. For the silver nanorod of length L=150 nm and radius a=7.5 nm, the magnitude and the phase of the polarization current at the resonance frequency f=260 THz computed by MBF technique are shown in Figs. 1(c-d). It illustrates the MBF technique converges by 5 MBFs, i.e., 5×5 matrix equation. This will allow an almost 3-orders of improvement in speed in compared to traditional methods. (MBF method takes 5 seconds whereas FDTD takes 5 hours on an Intel Core(TM)2 Duo at 2.2 GHz CPU frequency with 4.00 GB RAM).

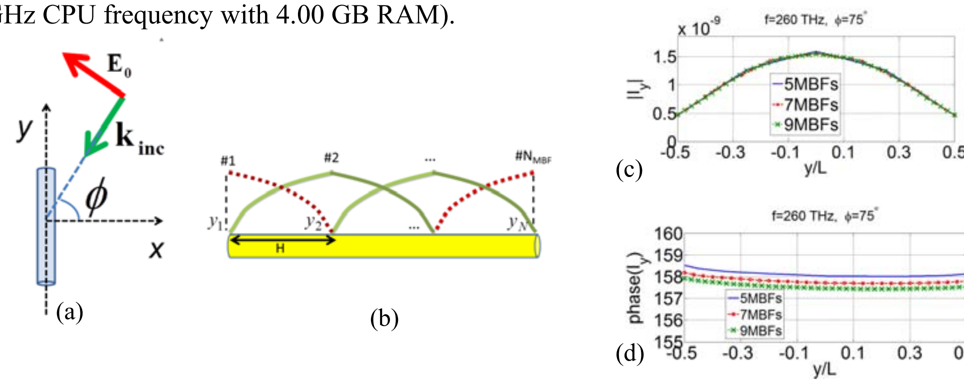


Fig. 1: (a) A plasmonic nanorod illuminated by an oblique planewave, (b) Discritization of the polarization current, (c) Magnitude and (d) Phase of the polarization for φ=75˚ and f=260 THz

Let us now consider the array structure illuminated by an arbitrarily incident plane wave, as illustrated in Fig. 2(a). To solve the scattering problem by CBFM the first step is to find the CBFs (which are high level and entire domain BFs) for the single nanorod in the unit-cell. The CBFs are calculated via a Singular Value Decomposition (SVD) procedure applied to the previously obtained MBFs, to reduce the number of unknowns further, for the isolated element (a nanorod) that are derived by using a number of incident fields with different wave vectors and polarizations. Next, we follow a procedure that begins by simulating a relatively small-size truncated array and derive a small-size matrix equation by using Galerkin's testing on the central element. Furthermore, we take advantage of the fact that the shape of the macro-CBF, comprising of a linear combination of the CBFs, remains essentially unchanged and its level only fluctuates as we increase the number of rings (see Figs. 2(b-d)). To determine the level of the macro-CBF, we take advantage of the rapid convergence of the Galerkin inner product when performed in the spectral domain by using the Parseval theorem. We obtain closed-form formulas for the reflection and transmission coefficients, as depicted in Fig. 2(e), by determining the contribution of the visible Floquet mode component of the scattered field in the spectral domain [6]. The more closer we get to grazing angle the less transmission is obtained. The loss of the plasmonic material also absorbs some part of the incoming wave. It must be mentioned that analysing such structure is a challenging task (due to long aspect ratio of the nanoantenna and its frequency dispersive material). The computational speed improvement using our model in compared to FDTD for normal and oblique incidence is about 2 and 4 orders of magnitude, respectively, on an Intel Core(TM)2 Duo at 2.2 GHz CPU frequency with 4.00 GB RAM, for 80 frequency samples.

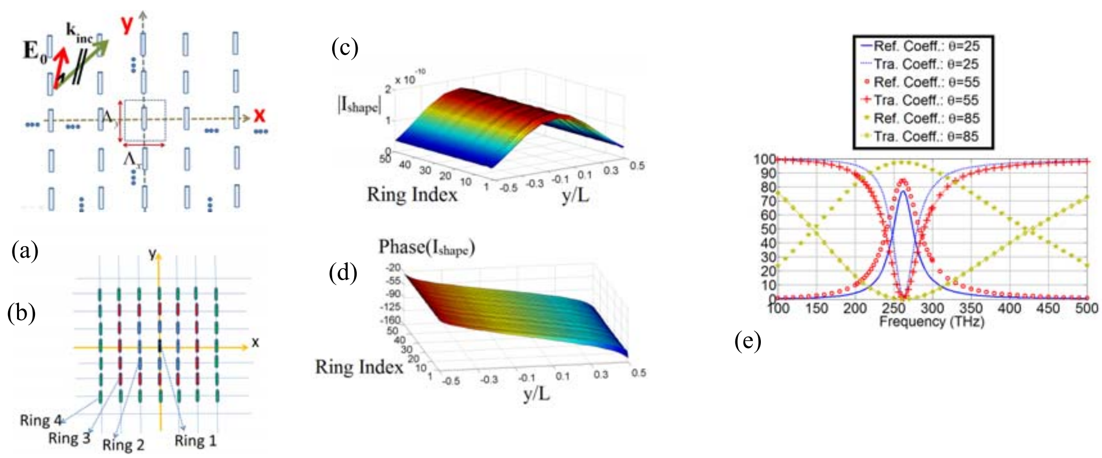
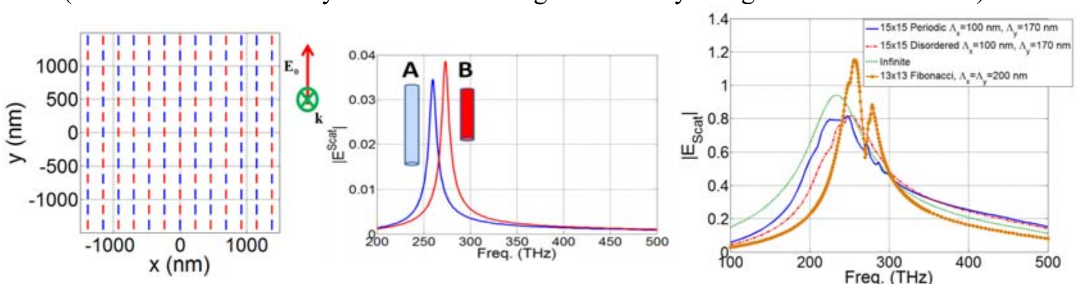


Fig. 2: (a) Array illuminated by an oblique wave, (b) Ring definition, (c) Magnitude and (d) Phase of the macro-CBF versus ring index and length of the nanorod, (e) Reflection and transmission coefficient for three different values of θ =25˚, 55˚, and 85˚.

We are now in the position to successfully solve a non-periodic array of plasmonic antennas. This has great benefit as novel combinations of resonant elements (not in a periodic fashion) can open up unique opportunities [7]. Further one is always interested to explore the effect of disorder in a fabrication. Towards this the performances of finite disordered array and Fibonacci quasi-lattice of nanorods are explored. For the disordered array, we consider a 15×15 array with a random disorder in which each of the nanorods is randomly tilted around its centroid. The tilted angle between the direction of each of the nanorods and the *y*-axis varies randomly between $\pm 30^{\circ}$. For the Fibonacci a 13×13 array of order 6 as depicted in Fig. 3(a) is used (F_6=**ABAABABAABAAB,** where **A** and **B,** are two plasmonic nanorods with the same radius but different lengths). We design two plasmonic nanorods **A** and **B**, to have the resonant frequencies at f_A=260 THz and f_B=1.05× f_A =273 THz. The CBFM is applied to find the frequency response (see Fig. 3(b)). Figure 3(c) illustrates the performance for the periodic and disordered finite arrays (15×15), and the 13×13 Fibonacci quasi-lattice. We also present the results for the infinite periodic array. For the Fibonacci array, the frequency response can be described as a blend of two resonant response illustrated in Fig. 3(b). Physically if we bring the elements closer to each other, the two resonant frequencies merge to each other and an optimized design with broadband characteristic can be achieved. The modeling of the proposed large arrays takes about 6 min/40 frequency samples on the machine Alienware i7-3.47 GHz CPU with 8.00 GB RAM over the entire frequency band (while it should take days to solve such large finite array using traditional methods).



(a) (b) (c)

Fig. 3: (a) 13×13 Fibonacci Array, (b) Scattering performance of the **A** and **B** nanorods, (c) Optical performance of finite periodic, disordered, infinite and Fibonacci arrays.

3. Conclusion

We demonstrate a fast and powerful computational model for successful characterization of large arrays of plasmonic nanorods antennas. This is a physics-based model where one unit cell of the metamaterial is analyzed utilizing only few basis functions. Orders of magnitude improvements in speed and memory are achieved. The physics of periodic and non-periodic configurations are studied.

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