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A comparison of the absorbed power for periodic, disordered and deterministic aperiodic arrays of Silver nanoparticles

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Abstract. The comparison between the optical properties of ordered and disordered metallic nanoparticles (NP) on the top of a silicon substrate has been studied. Such structures have been used to enhance the performance of optoelectronic devices, by exploiting the properties of the metallic NPs and their interaction with each other. This comparative study has been carried out using the Finite Difference Time Domain (FDTD) numerical analysis. Here, we report the role of distributed NPs on a silicon substrate and the electric field coupling between them. A slab of silicon substrate with a size of the micrometer range has been taken. Several metallic NPs have been distributed on the surface of the silicon. This structure has been studied for both periodic and disordered arrays of metallic nanoparticles. These NP's have been chosen as silver for which they exhibit strong localized surface plasmon resonance (LSPR). Total absorbed power has also been studied. The structure is illuminated by a plane wave source with a wavelength range that varies between 300 nm to 800 nm.

1. Introduction
Plasmonics is a new branch of research, which can be engineered into novel photonic and optoelectronic devices [1-6]. The unique electronic and optical properties of plasmonic nanoparticles (NP), specifically the localized surface plasmon resonance (LSPR) phenomenon are the core of plasmonic research [7-10]. The LSPR of the silver (Ag) NPs emerges from the interaction between the joint oscillation of conduction band electrons and incident electromagnetic radiations confined to the nanoscale [11]. LSPR extinction is a maximum when the frequency of the incident light and the free in the nanoparticles are matched [12,13].

The light matter interaction discussed, provides various results depending on the orientation of the NP medium. Ordered nanoparticles show distinct resonances, which can be controlled by the period of nanoparticles and spectrally red-shifts due to the phase alignment of scattered fields between neighboring particles [14]. If we consider deterministic aperiodic (DA) plasmonic structures, generated by mathematical sequences and number theory [15-19], it provides unique light localization and transport properties connected with the complex aperiodic structures [20-22].

In this work, a comparative study of the periodically and aperiodically oriented nanoparticles have been performed using the Finite Difference Time Domain (FDTD) method. The discussion will be focused on the power absorption of the plasmonic nanostructure and how it is affected by size, periodicity and the DA arrays. Random structures have also been considered, which provide a whole different result than the periodic or DA arrays [23]. The analysis will be focused on the power absorption of DA arrays, produced with respect to the Thue-Morse sequence.

2. Simulation Methodology
Figure1 shows the proposed plasmonic nanostructure. The Ag NPs are arranged periodically over a glass substrate. The nanostructure is illuminated by a plane wave source of the wavelength range 200nm – 800nm.
For such sub-wavelength metallic NPs, the interaction between them affects the absorption of light. Due to their plasmonic properties, multiple resonant modes are observed. For the nanostructure to behave as a photodetector, single resonant modes should be expected as results. To get single resonant modes, the periodicity of the Ag NPs must not be maintained, instead random arrays (figure 2b) or deterministic aperiodic (DA) (figure 2c) arrays can be used. This optimization of Ag NP distribution significantly changes the power absorbed. The nanostructure is simulated using the numerical FDTD solutions software [24], a commercial electromagnetic solver based on the FDTD method. As mentioned above, both periodic and random nanostructures have been considered.

For the FDTD region, the boundary conditions are anti-symmetric for x-axis and symmetric for y-axis. The z-axis has the perfectly matched layer as boundary condition. The non-uniform meshes are applied in the entire simulation domain. The mesh size in the regions around the NPs is $\Delta x = \Delta y = \Delta z = 2 \text{ nm}$ and the mesh size in the silicon region is $\Delta x = \Delta y = 1 \text{ nm}$ and $\Delta z = 2 \text{ nm}$. The incident plane wave propagates from up to down in the z-direction. The transmission of optical energy is defined as the light power flowing into the substrate normalized by the incident light power. Ag has been used as the metallic NP since they are widely recognized for plasmonic research.

3. Results and Discussion

Figure 3 shows the effect of Ag NP diameter on the absorbed power of the nanostructure. The increase of the diameter leads to the formation of multiple resonant mode. For NPs smaller than incident wavelength, electromagnetic field is uniform across a particle such that the conduction electrons move...
in phase producing only dipole-type oscillations, resulting in single narrow surface plasmon resonance (SPR) peaks. As the size of the NP increases the gap between them decreases. Several resonant modes are now created at longer wavelengths. The field across each particle becomes non-uniform and this phase retardation broadens the dipole resonance, exciting higher multiple resonance.

Figure 4 shows the change in absorbed power when the NP orientation is random. The curves have only a single resonant peak from 50nm to 125nm NP diameter. Since energy of random systems can be discrete, disordered induced localized states appear at discrete resonant frequency, where the electronic or optical diffusive transport breaks down. For 150nm NP diameter, the increase in size decreases the gap between the randomly oriented NPs. The nanostructure now starts behaving like the periodically oriented one and creates a secondary resonant mode.

**Figure 3.** The total absorbed power versus wavelength study of periodically arranged Ag NPs on glass substrate for NP diameter ranging from 50nm to 150nm.

**Figure 4.** The total absorbed power versus wavelength study of randomly arranged Ag NPs on glass substrate for NP diameter ranging from 50nm to 150nm.

The Thue Morse sequence has been used as a deterministic aperiodic system and was found to provide the best result for the absorbed power (figure 5). Though it has shown some small resonant modes in
the lower wavelength region, the total absorbed power had the greatest peak in the 350 nm region compared to the periodic and disordered arrays of NPs, resulting in lower power losses.

![Figure 5](image)

**Figure 5.** The total absorbed power versus wavelength study of Thue Morse array of Ag NPs on glass substrate for NP diameter of 50nm.

4. Conclusions
Comparing ordered NP’s distribution with disordered ones, it is seen to produce less resonant modes for the latter one. The disordered array of NP’s resembles the diffuse diffraction spectra of amorphous structures, that is, resulting in single resonant modes. Only for a diameter of 100 nm for the silver NP’s, a second resonant mode of lower absorbed power than the primary resonant mode has been observed in the higher wavelength region. The ordered plasmonic nanostructure is thus ideal for use in photovoltaic applications whereas the random or deterministic aperiodic plasmonic nanostructure can be put into application as UV detectors due to peaks formed around the UV range.

References

[1] Berry C W, Wang N, Hashemi M R, Unlu M, and Jarrahi M 2013 *Nature Communications* **4** 1622
[2] Politano A 2012 *Philosophical. Magazine* **92** (6) 768–778
[3] Bao Q and Loh K P 2012 *ACS Nano* **6** (5) 3677–3694
[4] Politano A and Chiarello G 2013 *Nanoscale* **5** 8215–8220
[5] Politano A 2012 *Plasmonics* **7** (1) 131–136
[6] Lakowicz J R 2006 *Plasmonics* **1** (1) 5–33
[7] Wang J and Zhou H S 2008 *Analytical Chemistry* **80** 7174–78
[8] Jin Y and Gao X 2009 *Nature Nanotechnology* **4** 571–76
[9] Lal S, Link S and Halas N J 2007 *Nature Photonics* **1** 641–48
[10] Hiep H M, Yoshikawa H and Tamiya E 2010 *Analytical Chemistry* **82** 1221–27
[11] Xie T, Jingga C and Yi-Tao Long 2017 *Analyst* **142** 409–20
[12] Stewart M E, Anderton C R, Thompson L B, Maria J, Gray S K, Rogers J A and Nuzzo R G 2008 *Chemical Reviews* **108** 494–521
[13] Nehl C L and Hafner J H 2008 *Journal of Materials Chemistry* **18** 2415–19
[14] Lamprecht B, Schieder G, Lechner R T, Ditlbacher H, Krenn J R, Leitner A and Aussennegg F R 2000 *Physical Review Letters* **84** 4721–24
[15] Queffelec M 1987 *Substitution dynamical systems-spectral analysis*, Lecture Notes in Mathematics, (Springer: Berlin, 1987) **1294** ISBN-978-3-540-18692-2 (Print) 978-3-540-48088-4 (Online)
[16] Macia E 2006 Reports on Progress in Physics 69 397-441
[17] Williams S G 2002 Symbolic dynamics and its applications American Mathematical Society (Short Course, January 4-5, 2002, San Diego, California) 60
[18] Schroeder M R 1985 Number Theory in Science and Communication (Springer-Verlag Berlin Heidelberg ), ISBN 978-540-26598-6
[19] Prusinkiewicz P and Lindenmayer A 1990 The Algorithmic Beauty of Plants Springer, New York, 1990
[20] Janot C 1997 Quasicrystals: A Primer 2nd ed. Oxford University Press, New York, 1997
[21] Dulea M, Johansson M and Riklund R 1992 Physical Review B 45 105–14
[22] Kroon L, Lennholm E and Riklund R 2002 Physical Review B 66 094204
[23] Forestiere C, Miano G, Boriskina SV, Dal Negro L 2009 Optics Express 17(12) 9648-61
[24] Lumerical Solutions, Inc. 3 http://www.lumerical.com/