Enhanced Optical Antennas with Fractal Metasurface

Yizhe Fan

Abstract. Plasmonic is now a quickly expanding area of research for its versatile in a lot of areas with its perfect ability of confining EM waves and trapping light. Periodic metallic structures are excellent to manipulate the properties of the SPPs by modifying the geometry of the pattern. In this project, we demonstrate a kind of fractal metasurface based on Sierpinsky Nanocarpet to simulate a higher absorption peak and electric field enhancement. We experimentally change the dimension level, size, thickness and separation distance in order to study the geometry dependency of the photosensor. Compared to several different fractal metasurface, the optimized structure proposes an approximately 30% enhancement in light absorption compared to a common log38 Sierpinsky Nanocarpet structure.

1. Introduction

Plasmonic is now a quickly expanding area of research for its versatile in a lot of areas. Plasmonic have been proved to be a very powerful tool in nano imaging, bio-sensing, energy harvesting and communication areas. Confining the EM wave close to the surface of the material can help us improve the energy harvesting efficiency and improve the imaging quality[1].

The surface plasmon enhancing photodetectors[2] is mainly due to the surface plasmon structures and the adjustment of the light absorption in active layer. When the photon energy of a particular optical band is greater than the band gap width of the active layer, the absorbed photon can generate electron hole pairs and thus generate photo-current. The excitation of localized surface plasmon resonances leads to substantially enhanced and highly localized electromagnetic fields[4].

Metamaterials (MTMs) have recently attracted widespread interest due to their extraordinary physical properties and potential applications[5]. The metal nanoparticles can be embedded into the surface of the detector without compromising the architecture of the device, which makes it popular in designing fractal photo sensors. And it’s worth mentioning that as metal nanoparticles grow in size, the light scattering ability of nanoparticles is also constantly enhanced. So the strong scattering properties of metal nanoparticles can be used to improve light absorption of photoelectric sensor, however, when the size of the metal nanoparticles increases to a certain value, there will be delay effect and the increase of the high order multipolar incentive mode, scattering rate appeared a downward trend.

Various techniques were introduced to excite surface plasmons, like prism coupling, focused beam coupling and grating coupling. People find periodic metallic structures are excellent to manipulate the properties of the SPPs by modifying the geometrical dimensions of the pattern. A fractal is a geometrical shape whose parts resemble, at least statistically, the whole. This often makes fractals self-similar, i.e. parts look like each other and like the whole object[5]. The geometry dependency of those structures attracted researchers to optimize those structures for specific applications. Recently, a new type of plasmonic structures called fractal plasmonic structure, was proposed by Volpe’s group[4]. After the first fractal “Koch snowflake” introduced by Helge von Koch in 1904[6], various kind of fractals came
into being. The fractal geometry we are going to study is “Sierpinski carpet” introduced by Waclaw Sierpiński in 1915, which is a milestone in the development of the fractal area. The structures of the Sierpinski Nanocarpets[4, 7] in the above articles was simple and monotony. In fact, until now, only one type of the Sierpinski Nanocarpets ($D=\log_3 8$) was studied.

Fractals, unlike other symmetrical geometries, have its unique optical properties such as multiband property and high localized intensity. In this letter, we studied various types of the Sierpinski Nanocarpet. For the optical response in strongly depend on the geometry and the dimension of the fractal pattern, the simulation plan was divided to four parts. Fractal generated here used bottom-up method by arranging the monomers to special array. By changing the size of the monomers, I planned to figure out the monomer size dependency of optical absorption. The next part is study of monomer’s thickness and separation dependency. The monomers constructed the fractals have certain separation distance between each other. By the way, we have to notice the separation distance also have self-similarity feature as we increase the level of the fractal. The modifying of the separation distance between the monomers was also expected to have some light absorption varying. Level dependency was studied by modifying the complexity of the fractals. This part was also designed to replicate the results showed in Volpe’s paper to ensure the validity of my simulation results. Dimension dependency was the most interesting and complex part of the simulation. Several new types of the fractal plasmonic structures were proposed in this part. Those fractals with different Hausdroff dimensions will show different features of light trapping.

2. Results and Discussion

The numerical simulation tool I used for this project is FDTD solution, which is an ideal tool for fractal plasmonic simulation for its high efficiency and accessibility to script language. Bottom-up building method for fractal pattern can waste a lot of time without the script language. FDTD solution allowed me to generate and modify the fractal geometry easily by simply change the predefined parameters.

To reveal the relation between Hausdroff dimension and optical response of Sierpinski Nanocarpet, I have also generated several new types of the Sierpinski Nanocarpet except $D=\log_3 8$. The creation of new Sierpinski Nanocarpet is not that hard by simply adjusting the filling element on the lattice points. The basic criteria of generating new geometry is retain its spatial symmetry. This is because the application of optical trap favors symmetrical field profile. In this project, I generated 8 types of Sierpinski Nanocarpet (Figure 1) with different fraction and levels. The dimension is determined by the fraction and the iteration level. The geometries present here is only a small part of the possibilities. Some of the geometries seems sparse in distribution of nanoparticle ($\log_3 5$, $\log_3 4$, $\log_3 16$ for example). Others have some changes in iteration level and numbers of particles per array to obtain a higher density. However, limited by the computation power I can access, geometry with higher complexity is not listed and the levels of the geometry is limited below 4.
Figure 1 Various types of Sierpinski Nanocarpet

The complex fractal geometry start up by a simple cube called monomer (Figure 2). The material I used for the structure is gold. The optical parameters of gold were obtained from Johnson and Christy’s experimental data. The dimensions of the cubic monomer were controlled by its lengths and thickness. The default properties of a monomer is set to 50nm in length and 35nm in thickness. The distribution density of fractal materials can be appropriately increased in order to increase the surface plasmon polariton propagation. Take the geometry D=log517 as example, the monomer was duplicated and arranged to fit into a 5*5 array. That’s why we define the fraction of the array is 5. Moreover, the amount of monomer fitting into one array is 17 so that the dimension is defined as log517. Then the array itself generated in this step will be treated as “monomer” to be duplicated and fitted in to the enlarged array to generate next level fractal. If we need higher level of the fractal, we can simply repeat this process for more times. But we have to notice that the higher levels of the fractal might requires larger memory to run the simulation and take longer computing time.

Figure 2 Bottom-up buildup of Fractal plasmonic structure (D=log517)

The area of simulation region was set to be 2.25 times of the total area of the fractal geometry. To simulate the scattering spectrum of the structure, I applied Total Field Scattering Field (TFSF) light source, which is an advanced type of plane wave source. Scattering intensity was collected by the horizontal monitor, which is placed outside the TFSF (The field outside the TFSF box was subtracted by the source field, where only remains scattering field.). In order to obtain transmission and absorption, a power monitor was placed below the device which returns the negative reflection. The absorption curve could be produced through the upper and lower power monitors, and then the normalized absorption curve could be calculated according to the size and interval of each Monomer. These operations can be used to determine the efficiency of the sensor.

To verify the validity of my model, level dependency of the optical response of the fractal plasmonic structure was simulated. The data collected in this part was also compared to the results presented in Volpe’s paper. The size of the monomer is set to be 50 nm×50 nm×35 nm and the separation distance is 5nm at first level, which is identical to Volpe’s setting. Level of the fractal ranges from 2 to 4, which marks the complexity of the geometry (Figure 3 (a)). To make a better comparison with the common structure of photodetectors, I also add some simulation results of D = log58 structure to see the difference between them (Figure 4 (a)). The wavelength of the light source was set between 300nm to 1.5um, which is between visible light to Near-IR. This result is very approximate to Volpe’s result. The deviation might originate from the difference of the simulation environment and mesh accuracy.

According to my simulation results of dimension log517, The fractal pattern of the second and third levels can obtain better absorption peaks, the highest absorption peaks appear at wavelength 704nm and
717nm. The fractal structure of the fourth level adopts the mesh accuracy with the accuracy of 2, and the obtained absorption curve however does not reflect fine light absorption and start to collapse. With increasing of the level of the Sierpinski Nanocarpet, I find the scattering peak is red-shifted and the FWHM is broadened. The prediction might be reasonable that in a certain range of iteration level, the scattering feature is independent from the fractal level with the premise that the level is sufficiently high. When it comes to $D = \log_38$, we can have a quite similar result that in the level 3 and level 4 curve, the scattering intensity gives a stable absorption peak at 719nm. However, the level 2 curve shows an apparent red shift. So I continued the simulation with $\log_517$ and $\log_38$ structures in level 3.

![Figure 3](image)

(a) Scattering Intensity of the Sierpinski Nanocarpet from my simulation data against iteration level ($D = \log_517$); (b) Scattering Intensity of the Sierpinski Nanocarpet against monomer’s thickness ($D = \log_517$); (c) Scattering Intensity of the Sierpinski Nanocarpet against monomer’s thickness ($D = \log_517$); (d) Scattering Intensity of the Sierpinski Nanocarpet from my simulation data against iteration level ($D = \log_517$).

Just like studying the iteration level, I have adjusted the size of the monomers to see what happened to the scattering spectrum of both $\log_517$ and $\log_38$ structures. It can be seen from the result that the monomer of 60nm in length perform a better light absorption than others. When the size of a monomer become smaller, the curve start to split as showed in the Figure 3 (b). However, the light absorption will no longer keep rising as we increase the size of the monomer. As for the $\log_38$ structure in Figure 4 (b), within the range of 35nm to 50nm, the scattering curve increases steadily with the increase in size of a monomer and the absorption peak reaches 0.43 in 697nm. After reaching 60nm, the absorption peak begins to split. The overall absorption rate is not as good as $\log_517$ structure.
In addition, we also study the effect of changing the thickness of the monomer. Firstly, when observing the results we obtained from log₁₇ structure we can tell that in an appropriate scope, the scattering intensity strengthened as we increase the thickness of each monomer combined with certain red-shifting phenomenon. The change of strengthen process become less significant when the thickness set up to 50nm. Similarly, in the graph of log₈ structure, with the increase of monomer’s thickness, the wavelength of the absorption peak is not greatly affected, and the scattering intensity in the image of log₈ also does not change greatly. So I came up with the assumption that the thickness does not have much effect on the light absorption of the overall photodetector, especially in log₈ structure. Finally, I choose the 60nm thickness as a optimized result which can slightly increase the efficiency of light absorption.

Finally, to figure out the relation between the separation distance of the monomers and the optical response of the structure, I simply modified the separation distance of the Sierpinski Nanocarpet with parameters set to the optimized monomer length(60nm) and thickness(50nm). I also made subtle adjustments to the separation length of each monomer. According to the results obtained for log₁₇ structure, the peak wavelength by adjusting different spacing is also different, which may be due to the change in the overall structure size of the device. So as the log₈ structure demonstrated in Figure 4 (d), although the scattering curves remain similar among separation distance of 4nm, 5nm and 10nm, the
curve split in 2nm and become not so selective in 10nm. To make a better selectivity and absorption rate, I finally take 5nm as the optimized separation distance of log517 structure.

What’s more, major scattering peak of 0nm’s separation distance is enhanced compared with the gaped geometry when I was modifying the log38 structure. So I decided to observe the electric field distribution of the two different structures. Something more interesting is that the superfocusing effect of smaller monomer separation distance become much stronger than the gaped one. As we can see from Figure 6, the “hot spot” of the gapless structure located at the center shows extremely high intensity. Among these results, I observed the electric field distribution of various structures to show the detector’s ability of light trapping. The results show that at peak wavelengths, a large amount of light is confined to the surface of the metal particles in the middle. This discovery also provided a pathway to obtain stronger optical trap.

Figure 5 The Electric field profile of the cross section of Sierpinsky Nanocarpet(D=log517).
10nm(top) 5nm(middle) 0nm(bottom)
Figure 6  The Electric field profile of the cross section of Sierpinsky Nanocarpet(D=log38). 10nm(left) 0nm(right)

I have tried to set up the relation between Hausdorff dimension and the scattering peak. The dimension vs scattering peak is listed in Figure 7. According to the simulation results, there is no obvious relation between the Hausdroff dimension and the position of scattering peak. By analyzing the E-field profile of the cross section of each structure, I figured out the “hot spot” will only form at the center the quasi-closed and hollowed geometries. The strongest “hot spot” appears in the fractal with dimension of log520 and log524.

| Dimension | D   | sqrt(D) | Scattering Peak [nm] | Scattering Intensity | Enhance Index |
|-----------|-----|---------|----------------------|---------------------|---------------|
| Monomer   |     |         | 532                  |                     |               |
| log3(5)   | 1.46| 1.20    | 601                  | 0.384               | 0.78          |
| log3(8)   | 1.89| 1.37    | 719                  | 0.495               | 1.00          |
| log5(24)  | 1.97| 1.40    | 777                  | 0.410               | 0.83          |
| log5(17)  | 1.76| 1.33    | 889                  | 0.644               | 1.30          |
| log5(21)  | 1.89| 1.37    | 868                  | 0.633               | 1.28          |
| log5(20)  | 1.86| 1.36    | 830                  | 0.451               | 0.91          |

After getting the simulation results of various structure, I compare the effect of light trapping by calculating the proportion as enhance index. The default standard is the common log38 structure. With dimension set to log524 and log517, we obtain an appropriate enhancement on the local electric field. In addition, log517 structure performed an enhanced light absorption by about 30% than log38 structure, indicating a better light absorption capacity. Therefore, the dimension of the optimized structure was set as log517, and the size of Monomer was set as 50nm in length and 50nm in thickness with the 5nm separation distance.
3. Summery
In this project, we simulated several new types of Sierpinski Nanocarpet. Size dependency, separation distance dependency and level dependency was discussed. Two major structures, $\log_{5}17$ and $\log_{3}8$ were made as comparison. We obtained an optimized structure of $\log_{5}17$ Sierpinski Nanocarpet with monomer size of $60\text{nm} \times 60\text{nm} \times 50\text{nm}$ and proved this structure can provide stable trapping for submicron particles, an approximately 30% enhancement compared to $\log_{3}8$ structure. Fabrication and characterization methods were also introduced to pave the path for experimental study. The broadband light trapping of the Sierpinski Nanocarpet enables this structure to be utilized in solar cell, which greatly improved energy harvesting efficiency. The superfocusing property of this structure can provide an ideal platform to realize optical trapping.

References
[1] Su Y, Guo Z, Huang W, et al. Ultra-sensitive graphene photodetector with plasmonic structure[J]. Applied Physics Letters, 2016, 109(17).
[2] Berini P. Surface plasmon photodetectors[J]. Proceedings of SPIE, 2013.
[3] Khoo, R. S. H. E. H. (2016). Broadband Optical Response in Ternary Tree Fractal Plasmonic Nanoantenna, 465–473. http://doi.org/10.1007/s11468-015-0059-3
[4] Volpe, G., Volpe, G., & Quidant, R. (2011). Fractal plasmonics: subdiffraction focusing and broadband spectral response by a Sierpinski nanocarpet, 19(4), 3612–3618.
[5] Tang, S., He, Q., Xiao, S., Huang, X., & Zhou, L. (2015). Fractal plasmonic metamaterials: physics and applications, 4(3), 277–288. http://doi.org/10.1515/ntrev-2014-0025
[6] Khoo, R. S. H. E. H. (2016). Broadband Optical Response in Ternary Tree Fractal Plasmonic Nanoantenna, 465–473. http://doi.org/10.1007/s11468-015-0059-3
[7] Puente-baliarda, C., & Romeu, J. (1998). On the Behavior of the Sierpinski Multiband Fractal Antenna, 46(4), 517–524.
[8] Kazerooni, H., & Khavasi, A. (2014). Plasmonic fractals: ultrabroadband light trapping in thin film solar cells by a Sierpinski nanocarpet, 751–757. http://doi.org/10.1007/s11082-013-9783-0
[9] Harada, Y. (1996). Radiation forces on a dielectric sphere in the Rayleigh scattering regime, 124(March), 529–541.
[10] Chen, T. L., Dikken, D. J., Prangsma, J. C., Segerink, F., & Herek, J. L. (n.d.). study Characterization of Sierpinski carpet optical antenna at visible and near-infrared wavelengths. New Journal of Physics. http://doi.org/10.1088/1367-2630/16/9/093024
[11] Wikipedia contributors. "Near-field scanning optical microscope." Wikipedia, The Free Encyclopedia. Wikipedia, The Free Encyclopedia, 14 Nov. 2016. Web. 14 Nov. 2016.