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Electric Field Enhancement by Two-scale Structure

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Abstract: We propose a novel multi-length-scale architecture for giant electric field enhancement. We investigate the capability of our structure to boost the electric field analytically and using full-wave simulations and verify our results with surface-enhanced Raman spectroscopy experiment.
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1. Introduction

Discrete chemical assemblies of metallic nanoparticles (oligomers) are well-known for providing strong near-field plasmonic coupling and giant field localization at subwavelength scale. These systems have found broad success as biosensors, in surface-enhanced Raman spectroscopy (SERS) and in optical integrated spectroscopy systems [1–3]. The enhancement obtainable by the oligomers depends on the size, shape, morphology and the local environment [2]. Unfortunately, the intrinsic nonlocality of the dielectric response of the metals along and their inherent loss limit the achievable field enhancement [4]. Hence, it is important to exploit additional mechanisms along with the plasmonic resonance to further increase the local field enhancement.

Periodic nanostructures, benefit from the coherent interaction of multiple scatterings from the elements [5]. The well-known Rayleigh anomaly occurs when the wavelength of the normal incident light matches the period of the structure which causes a sharp resonant-like behavior, called geometric resonance [6]. As a result, combining periodic structures with chemically assembled plasmonic oligomers is a promising avenue to further enhance the electric field. If the period matches to the LSPR wavelength of plasmonic oligomers, the Rayleigh anomaly may lead to a dramatic increase of the local field at the oligomers' field hot spot. Based on this, we propose a novel architecture to further enhance the electric field in the nanogaps. Our proposed structure, consists of chemically assembled oligomers of gold nanospheres with a nanoscale-sized gap between a periodic set of gold nanorods on a glass substrate, where the period of the structure is similar to the LSPR wavelength of the majority of oligomers. Appropriately, we call our synergistic design a two-scale structure since it involves two different methods with two different fabrication scales. In this work, we carry out a thorough study of this structure by using an effective numerical model and compare it to full-wave simulation results. We experimentally verify the ability of our structure to boost the electric field by exploiting the two-scale structure for SERS enhancement.

2. Analytical Model, Results and Discussion

Fig. 1(a), shows the schematic of our proposed two-scale structure, consisting of periodic gold nanorods and gold oligomers between them deposited on the glass substrate. Fig. 1(b), depicts the scanning electron microscopy (SEM) image of the structure shown in Fig. 1(a). Nanorod arrays were fabricated using standard electron beam lithography and a colloidal self-assembly method has been used for nanoparticles attachment [1]. To evaluate the ability of our proposed two-scale structure in boosting the electric field, we define the electric field enhancement as a figure of merit as $FE = \left|\mathbf{E}^{\text{tot}}(\mathbf{r})\right| / \left|\mathbf{E}^{\text{inc}}(\mathbf{r})\right|$ where $\left|\mathbf{E}^{\text{tot}}(\mathbf{r})\right|$ and $\left|\mathbf{E}^{\text{inc}}(\mathbf{r})\right|$ are the magnitude of the total and the incident electric field at an arbitrary location $\mathbf{r}$ respectively. Since our proposed architecture consists of two different scales, we can neglect the coupling from the oligomers to the nanorods, thus, the total electric field enhancement of the two-scale structure (FE_t) can be estimated as the product of the field enhancement by the periodic nanorods (FE_r) and the oligomers (FE_o) individually, $FE_t \approx FE_r \times FE_o$. For simplifying our analytical model, we assume a homogenous host medium for the two-scale structure. Moreover, we suppose that the incident beam is polarized along the nanorods, hence, each nanorod can be modeled as a current source [7]. The combination of incident beam and the scattered field of the nanorods, act as an external field to the oligomers. By applying single dipole approximation model [8], each nanosphere in the oligomer is modeled as an electric dipole and the total electric field in the middle of the gap spacing inside the oligomer (hot spot) is evaluated.

Specifically, we consider two exemplary cases here, each consisting of a linear trimer of gold nanospheres in the middle of periodic gold nanorods, whereas the trimer axis and the nanorods axes are parallel to each other. According to [9] the majority of oligomers have a resonance wavelength close to the linear trimer case. In both exemplary cases, the structure is illuminated by a plane wave polarized along the nanorods. In the first case, the two-scale structure is surrounded by vacuum and the diameter of nanospheres (d_s), the gap inside the oligomer (g), the diameter of nanorods (d_r) and their period (p_r) are 40 nm, 10 nm, 100 nm and 488 nm, respectively. The numerical results of the field enhancement versus wavelength for this case, is demonstrated in Fig. 1(c). Since the period of nanorods is the same as the linear trimer resonance wavelength, the Rayleigh's anomaly happens at the same wavelength as the LSPR wavelength and the field enhancement of the two-scale structure is the product of the field enhancement by the nanorods and oligomers individually. In the second case, the two-scale structure is deposited on top of a glass substrate and the diameter of nanospheres, the gap inside the oligomer, the diameter of nanorods and their period are 75 nm, 0.9 nm, 200 nm and 900 nm, respectively. Fig. 1(d), shows the full-wave simulation results of the field enhancement of the two-scale structure and the linear trimer individually versus wavelength. According to our simulation results, we expect to get 7-fold SERS intensity enhancement when the incident laser beam is at 785 nm and the Raman scattered light is at 850 nm with the two-scale structure (as shown in Fig. 1(a-b)) with same dimensions as Fig. 1(d). Our experimental results (for brevity not shown here but will be presented in the conference) are in agreement with our simulations and show 6-fold SERS intensity enhancement.

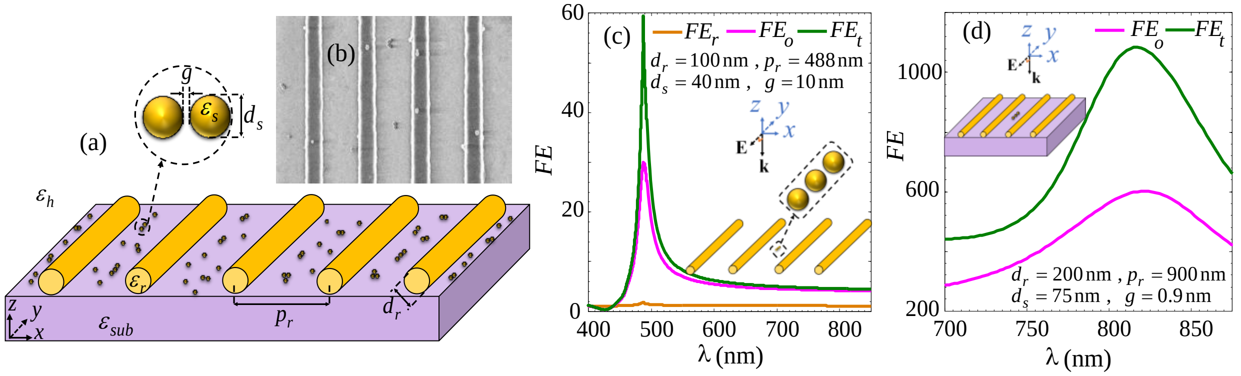

Fig. 1. (a) The schematic of the proposed two-scale structure and (b) the SEM image of the fabricated structure. The electric field enhancement versus the wavelength of incident plane wave of the two-scale structure (c) inside the vacuum host medium (d) on top of glass substrate.

In conclusion, by combining the plasmonic resonance of metallic oligomers and the geometric resonance of 1-D periodic nanorods, as the two-scale structure in Fig. 1, we further increase the achievable field enhancement by oligomers. We expect many applications such as medical diagnostics, solar cells, sensors, and single molecule detectors to benefit from the achieved large electric field enhancement values by the proposed two-scale structure.

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4. References

1. W. Thrift, A. Bhattacharjee, M. Darvishzadeh-Varcheie, Y. Lu, A. Hochbaum, F. Capolino, K. Whiteson, and R. Ragan, "Surface enhanced Raman scattering for detection of Pseudomonas aeruginosa quorum sensing compounds," in SPIE proceedings, Vol. 9550, pp.95500B–95500B–13 (2015).
2. M. Darvishzadeh-Varcheie, C. Guclu, R. Ragan, O. Boyraz, and F. Capolino, "Electric field enhancement with plasmonic colloidal nanoantennas excited by a silicon nitride waveguide," Opt. Express **24**, 28337–28352 (2016).
3. C. Nguyen, W. Thrift, A. Bhattacharjee, K. Whiteson, A. Hochbaum, and R. Ragan, "Robust SERS spectral analysis for quantitative detection of pycocyanin in biological fluids," in SPIE proceedingsVol. 10352, pp. 1035205-1035205-8 (2017).
4. C. Ciracì, R. T. Hill, J. J. Mock, Y. Urzhumov, A. I. Fernández-Domínguez, S. A. Maier, J. B. Pendry, A. Chilkoti, and D. R. Smith, "Probing the Ultimate Limits of Plasmonic Enhancement," Science **337**, 1072–1074 (2012).
5. B. Auguié and W. L. Barnes, "Collective Resonances in Gold Nanoparticle Arrays," Phys. Rev. Lett. **101**, 143902 (2008).
6. D. Maystre, "Theory of Wood's Anomalies," in *Plasmonics: From Basics to Advanced Topics*, S. Enoch and N. Bonod, eds. (Springer Berlin Heidelberg, 2012), pp. 39–83.
7. M. Kamandi, S.-M.-H. Emadi, and R. Faraji-Dana, "Integral Equation Analysis of Multilayered Waveguide Bends Using Complex Images Green's Function Technique," J. Light. Technol. **33**, 1774–1779 (2015).
8. M. Darvishzadeh-Varcheie, C. Guclu, and F. Capolino, "Magnetic Nanoantennas Made of Plasmonic Nanoclusters for Photoinduced Magnetic Field Enhancement," Phys. Rev. Appl. **8**, 024033 (2017).
9. W. J. Thrift, C. Q. Nguyen, M. Darvishzadeh-Varcheie, S. Zare, N. Sharac, R. N. Sanderson, T. J. Dupper, A. I. Hochbaum, F. Capolino, M. J. Abdolhosseini Qomi, and R. Ragan, "Driving Chemical Reactions in Plasmonic Nanogaps with Electrohydrodynamic Flow," ACS Nano **11**, 11317–11329 (2017).