Tunable Plasmon Resonance in Dual-Arm Plasmonic Bowtie Nanostructures

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Abstract **- Dual-arm nanobowtie nanostructures are proposed to achieve high E-field enhancement (EFE) with tunable plasmon resonance wavelength. The influence of the dual-arm position in the proposed nanostructures on their electromagnetic characteristics is investigated through FDTD modeling, which stands for Finite Difference Time Domain. This analysis aims to comprehend the plasmon resonance behavior exhibited by dual-arm bowtie nanostructures. Dual-arm nanobowtie nanostructures offer the potential to attain notably superior EFE at the central region of the structure compared to conventional single-arm bowtie nanostructures. We can further optimize the proposed nanostructure's geometry to achieve optimal high EFE values. The resulting high EFE factor and tunable plasmon resonance provides us various opportunities for tailored applications.**

I. INTRODUCTION

When a metallic nanoparticle is exposed to an external electric field, the interaction results in coherent oscillations of the conduction electrons, which is called localized surface plasmon resonance (LSPR)[1]. This phenomenon has been a major focus of various fields of nano-optics, especially in sensing applications. The electromagnetic behavior of LSPs is significantly influenced various properties like the dimensions, material, morphology, alignment, and ambient conditions of nanostructures[2-4]. These findings are of importance across various domains, including near-field optical microscopy [5], surface-enhanced Raman spectroscopy (SERS) [6-8], high-resolution optical imaging [9], and sensing devices [9-13], amongst others.

For the enhancement of the electromagnetic (EM) fields, various nanostructures have been previously proposed to achieve EM hotspots. Amongst the many proposed nanostructures, researchers have demonstrated that a bowtie-shaped nanostructure can be employed to achieve substantial EFE confined within the gap between two metallic triangular structures positioned against each other's tips with a small separation between them. [14-18].

In this paper, we present a variation of the conventional bowtie nanostructure — a dual arm gold nanobowtie shaped nananoantenna — to achieve high EM enhancement. We propose a dual-arm nanobowtie gold shaped nanostructure (Fig. 1) and demonstrate that the EM enhancement achieved in the proposed nanostructure is better than that of the metallic nanobowtie of similar dimensions. An exhaustive numerical analysis of the proposed engineered nanostructure is conducted by employing FDTD computations to calculate the EFE and the plasmon resonance wavelength for the dual-arm bowtie structure. Further, a detailed study of the effect of the position (KL) at which the kink is present (i.e., the position at which the second arm of the nano-bowtie is introduced, in the otherwise conventional single arm nanobowtie) on the EFE and the plasmon resonance wavelength is carried out to optimize the dimensions of the proposed nanostructure to obtain the desired EM behavior of the nanostructure. Fig. 1 shows the various geometrical dimensions of the proposed nanostructure.

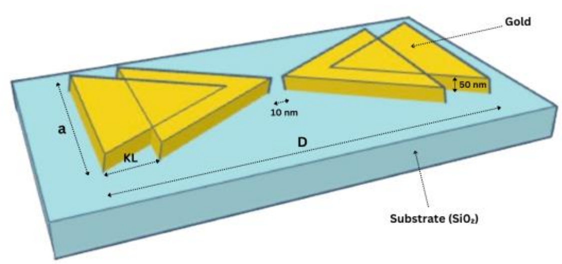

Fig. 1 Schematic depicting double-arm plasmonic bowties fabricated from gold(Au) metal with silicon dioxide (SiO_2) as chosen substrate with a gap 'G'=10nm, length 'D', thickness 'T'=50 nm, side of equilateral triangle 'a' and kink length 'KL'.

II. NUMERICAL METHODS

We employed a commercially available electromagnetic simulation software utilizing the FDTD method, to perform our simulations. A plane wave source with wavelength varying from 500 nm to 1800 nm was placed in the –z direction above the dual-arm bowtie nanostructure. The mesh size for the simulation was selected as 1 nm after careful convergence testing. The dielectric constant of all materials used are fitted by the Lorentz-Drude function We implemented Perfectly Matched Layers (PML) at all boundaries of the simulation domain. Gold (Au) was selected as the material for fabricating the double-arm plasmonic bowties due to its chemical stability, while silicon dioxide (SiO2) was chosen as the substrate. The gap between the triangular pillars of the dual-arm bowtie was set to 10 nm. The thickness of the dual-arm nano-bowtie pillars was taken as 50 nm for all simulations in this paper.

III. RESULTS AND DISCUSSIONS

In this paper, we have employed FDTD technique to study the electromagnetic behaviour of the proposed dual-arm nanobowties. Initially, we investigated the local EFE and the plasmon resonance wavelength of a conventional single arm bowtie nanostructure with the same dimensions as a standard for comparison. Subsequently, we numerically analyzed dual-arm plasmonic nanobowties with varying kink lengths, i.e., various positions at which the second arm is introduced in the proposed nanostructures.

Figure 2 shows the EFE maps for the various kink lengths, i.e., kink lengths varying from 72 nm to 30 nm. For this study, a constant double-arm bowtie length of 310 nm was maintained, and six kink lengths (15, 30, 45, 60, 69, 72 nm) were simulated. It is evident from the EFE profiles that the highest value for the EFE can be seen at the gap between the vertices of the dual-arm bowtie nanostructure with a kink length (KL) of 72 nm. This value is notably higher than that of the conventional single-arm bowtie structure (KL = 0 nm). Fig. 3 shows the EFE spectra for the various kink lengths of the proposed nanostructure, and it can be clearly observed that in addition to offering a higher field enhancement, the proposed nanostructure with dual arms can offer a tunable plasmon resonance wavelength varying from 926.582 nm to 1255.7 nm as the kink length is varied from 0 nm to 72 nm.

[21]. Additionally, to demonstrate the applicability of the proposed nanostructure for another wavelength regime, we also demonstrate numerical analysis for the proposed dual-arm nanobowtie nanostructure with a constant bowtie length of 260 nm, for which four different kink lengths (15, 30, 45, 60 nm) were simulated. It can be observed that the proposed nanostructure can achieve an EFE 57.0713, at a plasmon resonance wavelength of 1058.23 nm for kink length set as 60 nm. It must be noted that the sides of the triangular structures have been adjusted with varying kink sizes to keep the length of the bowtie constant.

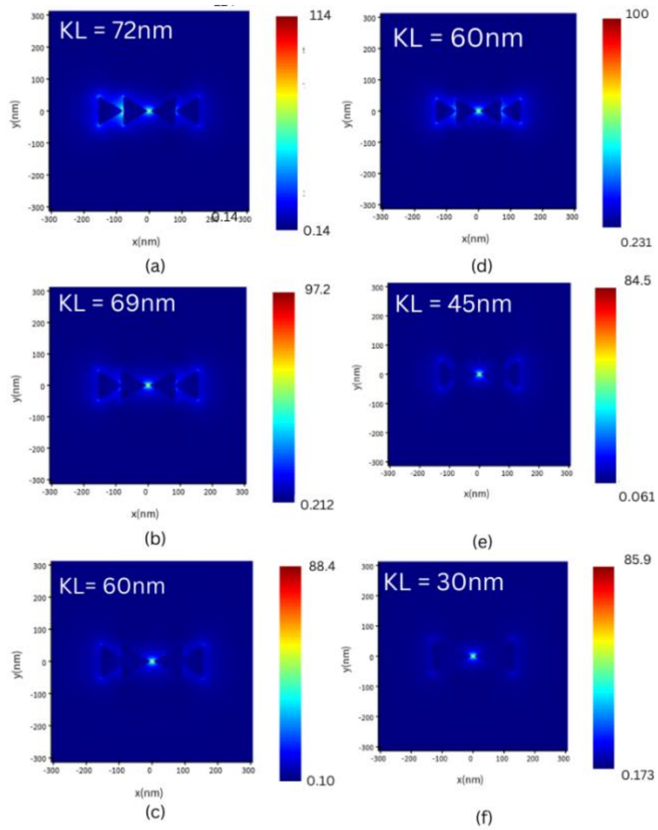

Fig. 2 EF profiles showing the EFE for different kink lengths (KL) of the double arm plasmonic gold nanostructure,with D = 310 nm. The side bars having a color range in the profiles demonstrate EFE (i.e., $|E|/|E_0|$).

Further, it can be seen from Fig. 3 that the prominence of the dual resonance peaks increases with the growing kink length of the double-arm plasmonic bowtie nanostructure.

With the kink length (KL) set to 0 nm as the reference, representing the single arm bowtie nanostructure, we initially observed a decrease in the EFE values of the nanostructures as the kink length was increased. The maximum decrease of 5.827% was observed at a KL of 45 nm. Subsequently, we noted an increase, with a significant rise of 25.15% observed for a KL of 72 nm. It is evident that the maximum EFE values for kink lengths of 69 nm and 72 nm in the double-arm bowtie structure are significantly higher compared to those of a simple bowtie structure, illustrating the utility of a dual-arm nanobowtie nanostructure. Similarly, for the bowtie structure with a length of 262 nm, we observed similar trends. The maximum decrease of 6.024% occurred at a KL of 45 nm. Subsequently, we noted an increase, with a significant rise of 13.85% observed for a KL of 60 nm. The effect of kink length on the EFE has been elaborated in Fig. 4 for the

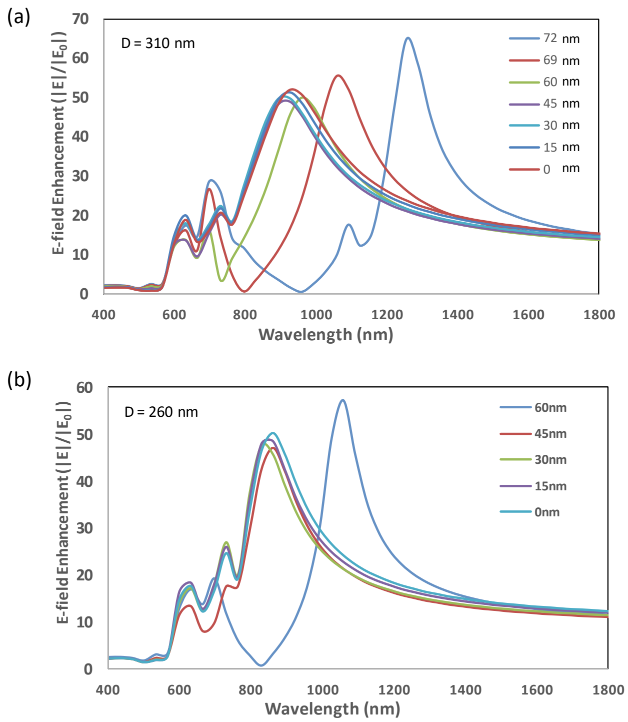

Fig. 3 Effect of the variation of the kink lengths (KL) of the double-arm plasmonic bowties on the EFE spectra with D, set to (a) 310 nm (b) 260 nm.

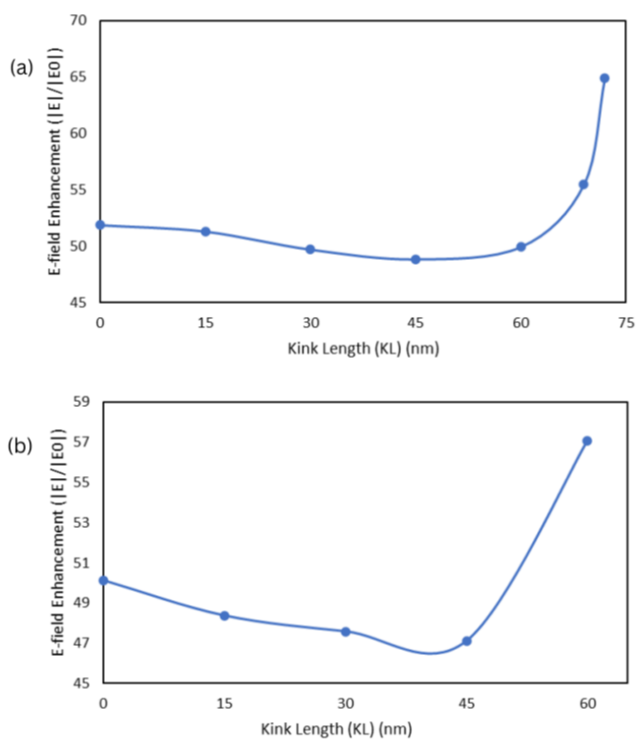

Fig. 4 Maximum values of EFE for the corresponding values of the kink lengths (KL) of the double-arm plasmonic bowties with the length of the structure, D, set to (a) 310 nm and (b) 260 nm.

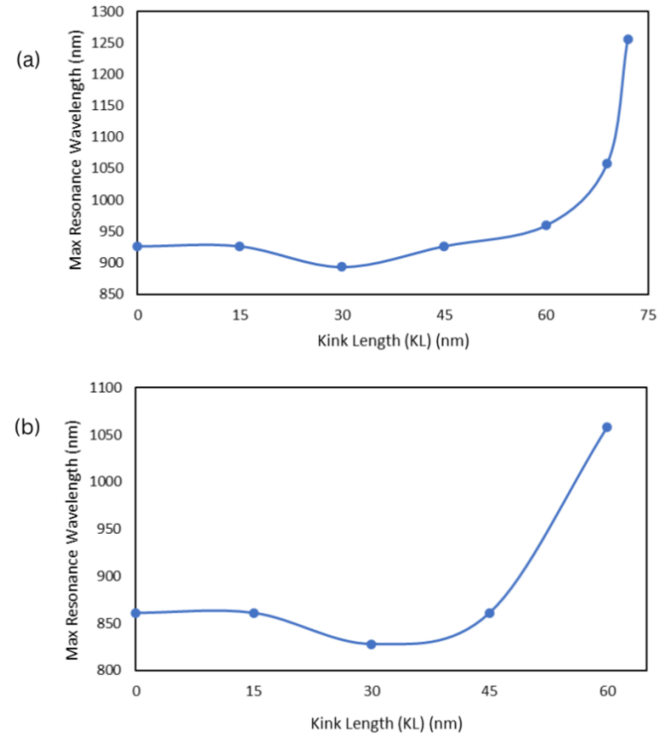

Fig. 5 Maximum seen resonant wavelength for the corresponding values of the kink lengths (KL) of the double-arm plasmonic bowties with the length of the structure, D, set to (a) 310 nm and (b) 260 nm.

length of the proposed nanostructure, D, being 310 nm and 260nm and on the plasmon resonance wavelength in Fig. 5. Hence, it can be concluded that dual-arm nano-bowties with higher values of kink lengths can be employed to achieve higher E-field enhancements along with a red-shifted plasmon resonance wavelengths. The proposed nanostructure opens a wide range of application possibilities such as surface-enhanced Raman scattering-based sensors, where high EFE values correspond to elevated SERS enhancement capabilities[22].

IV. CONCLUSIONS

The study systematically analyzed how the kink length in dual-arm nanobowtie nanostructures affects both the EFE and the plasmon resonance wavelength, aiming to understand their plasmon resonance behavior. The findings indicate that a dual-arm bowtie nanostructure exhibits tunable LSPR modes. We have achieved significantly better EFE at the center of the dual-arm bowtie as compared to the conventional single arm bowtie nanostructure. It can be inferred that optimal field enhancement is achievable through meticulous optimization of geometric dimensions. Hence, these critical dimensions present opportunities for tailored applications of such nanostructures across desired wavelength ranges.

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References

[1] Najem, Melissa. "Design, Fabrication, and Characterization of a Multimodal Optical Sensor with Nanostructures." Micro and Nanotechnologies/Microelectronics. Université de Montpellier, 2022. English. ffNNT: 2022UMONS082. Tel: 04117747.

[2] Liz-Marzán, L. M. (2006). Tailoring surface plasmons through the morphology and assembly of metal nanoparticles. Langmuir, 22, 32–41.

[3] Jensen, T. R., Malinsky, M. D., Haynes, C. L., & Van Duyne, R. P. (2000). Nanosphere lithography: tunable localized surface plasmon resonance spectra of silver nanoparticles. The Journal of Physical Chemistry B, 104, 10549–10556.

[4] Jensen, T. R., Duval, M. L., Kelly, K. L., Lazarides, A. A., Schatz, G. C., & Van Duyne, R. P. (1999). Nanosphere lithography: effect of the external dielectric medium on the surface plasmon resonance spectrum of a periodic array of silver nanoparticles. The Journal of Physical Chemistry B, 103, 9846–9853.

[5] T. Kalkbrenner, U. Hakanson, A. Schadle, S. Burger, C. Henkel, V. Sandoghdar, Phys. Rev. Lett. 95 (2005) 200801.

[6] F. Hao, P. Nordlander, Appl. Phys. Lett. 89 (2006) 103101.

[7] A. Otto, I. Mrozek, H. Grabhorn, W. Akemann, J. Phys.: Condens. Matter 4 (1992) 1143.

[8] J. Ye, M. Shioi, K. Lodewijks, L. Lagae, T. Kawamura, P. Van Dorpe, Appl. Phys. Lett 97 (2010) 163106.

[9] A. Cvitkovic, N. Ocelic, J. Aizpurua, R. Guckenberger, R. Hillenbrand, Phys. Rev. Lett. 97 (2006) 060801.

[10] John L. Bohn, D.J. Nesbitt, A. Gallagher, J. Opt. Soc. Am. A 18 (2001) 2998.

[11] N. Liu, M. Mesch, T. Weiss, M. Hentschel, H. Giessen, Nano Lett. 10 (2010) 2342.

[12] R. Ameling, L. Langguth, M. Hentschel, M. Mesch, P.V. Braun, H. Giessen, Appl. Phys. Lett. 97 (2010) 253116.

[13] Jian Ye, Pol Van Dorpe, Plasmonics 10 (2011) 665.

[14] R. D. Grober, R. J. Schoelkopf, and D. E. Prober, “Optical antenna, towards a unity efficiency near-field optical probe,” Appl. Phys. Lett. 70(11), 1354–1356 (1997).

[15] D. P. Fromm, A. Sundaramurthy, P. J. Schuck, G. Kino, and W. E. Moerner, “Gap-dependent optical coupling of single bowtie nanoantennas resonant in the visible,” Nano Lett. 4(5), 957–961 (2004).

[16] A. Sundaramurthy, K. B. Crozier, G. S. Kino, D. P. Fromm, P. J. Schuck, and W. E. Moerner, “Field enhancement and gap-dependent resonance in a system of two opposing tip-to-tip Au nanotriangles,” Phys. Rev. B 72(16), 165409 (2005).

[17] H. Guo, T. P. Meyrath, T. Zentgraf, N. Liu, L. Fu, H. Schweizer, and H. Giessen, “Optical resonances of bowtie slot antennas and their geometry and material dependence,” Opt. Express 16(11), 7756–7766 (2008).

[18] Kim, S., Jin, J., Kim, Y. J., Park, I. Y., Kim, Y., & Kim, S. W. (2008). High-harmonic generation by resonant plasmon field enhancement. Nature, 453(7196), 757–760.

[19] Sundaramurthy, A., Crozier, K. B., & Kino, G. S. (E. L. Ginzton Laboratory, Stanford University, Stanford, California 94305, USA). Fromm, D. P., Schuck, P. J., & Moerner, W. E. (Department of Chemistry, Stanford University, Stanford, California 94305, USA). Field enhancement and gap-dependent resonance in a system of two opposing tip-to-tip Au nanotriangles.

[20] Shu-Wei Chang, Chi-Yu Adrian Ni, and Shun Lien Chuang, "Theory for bowtie plasmonic nanolasers," Opt. Express 16, 10580-10595 (2008).

[21] Nien, L.-W., Chao, B.-K., Li, J.-H., & Hsueh, C.-H. Optimized sensitivity and electric field enhancement by controlling localized surface plasmon resonances for bowtie nanoring nanoantenna arrays.

[22] Bruzas, I., Lum, W., Gorunmez, Z., & Sagle, L. (2018). Advances in surface-enhanced Raman spectroscopy (SERS) substrates for lipid and protein characterization: sensing and beyond. Analyst, 143(17), 3990-4008.