Optical Resonance of Nanometer Scale Antennas with Coupling Structures

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Abstract — In this paper, the nanometer scale antennas composed of kinds of coupling structures are theoretically investigated focusing on their optical resonance characteristics. In particular, the bow-tie antenna and its geometrically complementary bow-tie shaped aperture antenna are both discussed for a comprehensive study. To demonstrate such structures, the finite integration technique is adopted to particularly provide broad band calculations covering the visible light and infrared region. Characterized by the surface plasmon resonance, localized strong field are found at the separation of the coupling antennas, thus leading to sufficient near-field confinement and enhancement. The resonant properties depending on the antennas' geometrical parameters are systematically determined as an extension and improvement of the existing studies. Taken the advantage of the concentrated optical field, these antennas have promising prospect in the applications in near-field optical detection or sensing, scanning probe microscopy, and optical devices.

I. Introduction

The nanoantennas for optical field enhancement applications have attracted extensive research interest both theoretically and experimentally [1], especially in the optics field. These nanoantennas are made of delicately designed and well-organized aligned nanometer scale noble metallic particles, such as gold, silver, and aluminum. Usually they are induced by plane wave excitation to provide the surface plasmon resonance in the visible and infrared frequency range. Nanoantennas perform their function of amplifying incident light in a focused area. Nanoantenna studies are important because of their unique light coupling capacity. This can lead to effective concentration and predominant confinement of light in the near-field [2].

Present nanoantenna research covers various designs. Among different configurations, we pay more attention to the resonant optical antennas with coupling structures, because the closely placed nanoparticle pair possesses predominance in field enhancement compared with a single particle [3]. The strong fields found near the sharp tips and in the gap between the two components of the antenna are highly dependent on the antenna structures, hence can be further tunable by controlling the geometric parameters for engineering exploration [4]. The intensively studied structures involve the bow-tie antenna, nanorods antenna and dipole antenna [5]. In the meantime, it is noted that bow-tie aperture antenna is effective to be applied as an aperture probe in near-field optical imaging [6]. However, to date there is not any comprehensive research simultaneously looking into both geometrically complementary nanoantennas to make a comparison. Therefore, our study is especially conducted on the spheroid-, rod-, cylinder-pair and two bow-tie shaped antennas to give insights into this area. In addition, the roles of the antenna's geometric parameters in changing the antenna resonance properties will also be illustrated in detail. Such a study is supposed to be helpful for further practical nanoantenna design and optimization.

II. Results and Discussion

A. Optical Properties of Coupling Antennas with Various Shapes

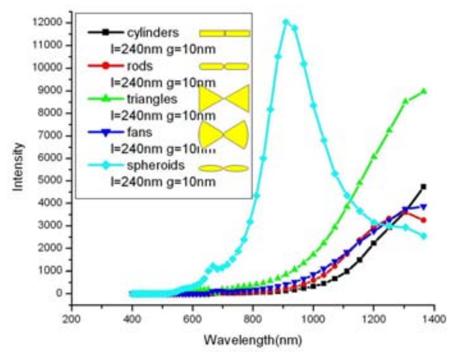

Fig. 1. Light intensity spectra of different shapes of pairs with the same length under the influence of shape

Fig. 1 shows the light intensity of different shapes of pairs (spheroids, cylinders, rods, triangles and fans) with the constant length of 240 nm and spacing of 10 nm. The source is a plane wave with unit E vector in the direction of longitudinal direction of the pair. By developing a finite integration technique covering 400~1400 THz frequencies, the light intensity value considered as the square of the magnitude of the E-field is calculated. It is computed at the fixed position in the middle of the gap separation between both antenna components.

In the computation, localized strong enhanced field is found inside the gap region of all the structures. This can be explained using lightning rod effect theory in electrostatics, which means sharp corners concentrate static charge, thus resulting in the largest electric field near the sharpest surface or sharp ends of nanoparticles. All the antennas' spectra exhibit a resonant manner p, which is expressed as several dramatically enhanced strength crests. Each maximum point can be considered as the resonance point of such nanoantenna. The light intensity shown can reach a peak ~3000 unit for all the structures except for the spheroids. Among them, triangles' intensity rises at fastest rate. So we use it as demonstration in Section C. The spheroids' light intensity at resonance is most pronounced over the considered frequency range. The highest value 12037 is approximately 84 times than that of the cylinders at the same frequency.

B. Optical Properties of Nanometer Scale Bow-tie Antenna and Bow-tie Shaped Aperture Antenna

Fig. 2 plots the light intensity of both bow-tie and bow-tie shaped antennas calculated in the optical range under the same excitation. We found that the value for aperture antenna is much lower than that of the bow-tie antenna at corresponding frequency position. In order to make a comparison between two complementary antennas, the field distributions near the antenna are also simulated, which is shown in Fig. 3. It is noted that the light focused area is different for two cases.

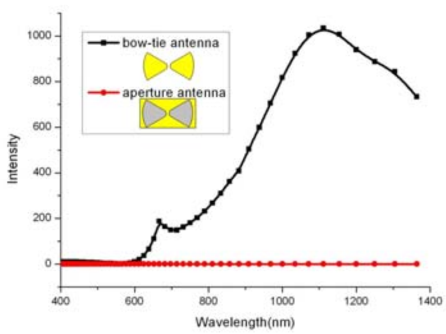

Fig. 2. Light intensity spectra of bow-tie antenna and complementary aperture antenna

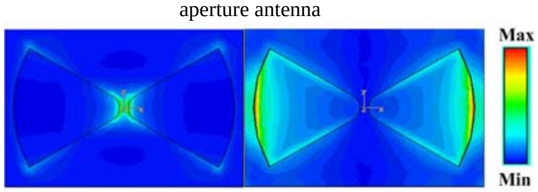

Fig. 3. Field comparison of bow-tie antenna and complementary aperture antenna

C. Optical Properties of Coupling Antenna Depending on Geometric Effects

The results for the coupling antenna's light intensity dependent on the length and spacing are given in Fig. 4. The triangle shape is taken as an example. The light intensity of two particle pairs at resonance is largely enhanced compared with a single particle or its double value. Higher intensity is obtained with either longer structure assuming the same gap spacing or closer placed structure assuming the same length.

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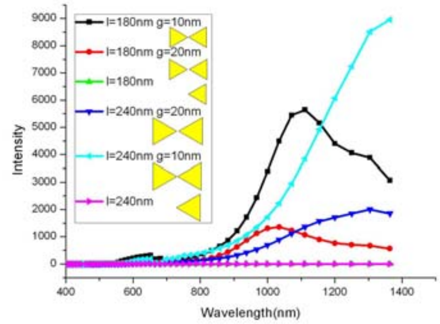

Fig. 4. Light intensity spectra of coupling triangles pairs under the influence of different length and gap spacing

III. Conclusion

The optical resonance characteristics of several nanometer scale antennas with coupling structures have been theoretically studied. The nanoantennas with the shapes of spheroids, rods, cylinders, triangles and fans all exhibit the excitation in a resonant manner inside the gap region at the infrared portion of the light spectrum. This is the fundamental of how an antenna works in the optical region. In infrared range, triangle shape coupling antenna gains most satisfying enhancement among all the considered coupling structures. To address the obstacle of inaccuracy data employed in previous study which limited their effective applicable frequency band, we improved this aspect by finite integration algorithm and applied more appropriate data for wide band computation. The antenna's optical resonance properties are found to be dependent on the geometrical parameters: narrower gap and longer structure supports higher intensity. The bow-tie antenna has better enhancement factor than the aperture antenna with the same complementary structure under the same excitation conditions. More exploration can be conducted in the lab using available laser sources for next step's study.

IV. References

[1] Z. Zhang, I. D. Mayergoyz, N. A. Gumerov, and R. Duraiswami, "Numerical Analysis of Plasmon Resonances in Nanoparticles Based on Fast Multipole Method," *IEEE Trans. Magn.,* vol. 43, pp. 1465-1468, 2007.

[2] M. Gu, P. Bai, and E. P. Li, "Enhancing the reception of propagating surface plasmons using a nanoantenna," *IEEE Photon. Technol. Lett.* , vol. 22, pp. 245-247, 2010.

[3] E. Cubukcu, N. Yu, E. J. Smythe, L. Diehl, K. B. Crozier, and F. Capasso, "Plasmonic laser antennas and related devices," *IEEE J. Sel. Topics Quantum Electron.*, vol. 14, pp. 1448-1461, 2008.

[4] H. Fischer and O. J. F. Martin, "Engineering the optical response of plasmonic nanoantennas," *Opt. Express,* vol. 16, pp. 9144-9154, Jun 2008.

[5] M. Gu, P. Bai, and E. P. Li, "Enhancing the reception of propagating surface plasmons using a nanoantenna," *IEEE Photon. Technol. Lett.*, vol. 22, pp. 245-247.

[6] Y. M. Wu, L. W. Li, and B. Liu, "Gold Bow-Tie Shaped Aperture Nanoantenna: Wide Band Near-field Resonance and Far-Field Radiation," *IEEE Trans. Magn.*, vol. 46, pp. 1918-1921, 2010.