

# Coupled two aluminum nanorod antennas for near-field enhancement

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**Abstract** Aluminum (Al) plasmonic nanoantennas possess many tunabilities in the ultraviolet (UV) region and have a variety of new applications, such as in sensitive UV photodetection and UV photolithography. Using discrete dipole approximation (DDA), the resonant optical properties and enhanced local field distribution of coupled Al nanorod antennas were investigated. The effects of gap distance on the extinction spectra were analyzed to obtain the surface plasmon modes of these nanostructures across the visible and in the UV spectral range, which can be attributed to the coupling of the surface plasmon modes from each Al nanorod. In addition, the enhanced local field factors plotted as a function of gap distance were simulated under transverse and longitudinal polarizations to achieve maximum near-field enhancement for the optical antennas. When the gap distance was decreased to 5 nm, the maximum value of the enhanced factor was 18.04 at the transverse mode peak of 424 nm. This could be explained by the combination of the interaction between the charges distributed at the opposite ends of two Al nanorods and the interaction between the charges distributed at the lateral sides of each Al nanorod. Results showed that the coupled Al nanorod antennas with enhanced local field show promise for UV plasmonics.

**Keywords** aluminum (Al) nanorod, optical antennas, surface plasmon resonance (SPR)

## 1 Introduction

Optical antennas can improve the interaction between the object and the incident light by using near-field coupling to convert the light from free space to the nanoscale areas and to enhance the local field [1,2]. The utilization of optical

antennas effectively concentrates the energy of the electric radiation in the nanometer scale, which can potentially enhance spontaneous emission, near-field nanolithography, and sensing applications. Metal nanoparticles have been used as optical antennas because of their ability to produce giant field enhancement and confinement for surface plasmon modes [3–5]. Their particle surface plasmon resonances (SPRs) are highly dependent on the material composition, the particle's shape, and the near- and far-field interactions of an individual antenna with neighboring nanoparticles [6,7]. Therefore, optical antennas with different shapes, such as bowtie, H-shaped, sandwiched, and slot antennas, have been designed for various applications in plasmonic devices and biosensors [8–10]. Among these nanostructures, the optical nanorod antenna with sharp edges has been observed to provide higher charge density, and thus generate a larger local field because of the lightning rod effect [11]. In addition, the gap between optical antennas based on metallic nanoparticles can result in strong field enhancement [12]. Moreover, certain methods, such as antenna arrangement and antenna array for improved coupling, have been proposed to maximize the field enhancement by tuning the resonance wavelength of optical antennas [13].

Unlike the familiar noble metals (Ag and Au), aluminum (Al), which has a d-band higher than its Fermi energy, can sustain SPRs beyond the visible region and into the ultraviolet (UV) region of the spectrum, which makes Al an appealing material for UV plasmonics [14–17]. Furthermore, Al is a popular kind of relatively economical and manipulable optical material, which shows promise in large scale production [18,19]. These advantages make Al nanorod optical antennas very attractive in a variety of applications, such as sensitive UV photodetection, UV photolithography, and enhanced UV fluorescence [20,21]. Propylene glycol methyl ether acetate (PGMEA), a good organic solvent, is generally applied as a photoresist thinner in nanofabrication. Introducing the PGMEA solution enables the modification of the optical properties

of metal nanoparticles, thus improving their functionality in some applications.

In this paper, the near-field optical properties of coupled Al nanorod optical antennas in an end-to-end orientation were theoretically investigated using discrete dipole approximation (DDA). The effects of gap distance on the extinction spectra were analyzed, and the enhanced near-field factors plotted as a gap distance function with two polarizations were simulated. With the resonance wavelength obtained from varying the gap distance and polarization, results showed that the antennas supported two resonances and produced high field enhancements, thereby providing very promising applications in UV resonances.

## 2 Methods

The extinction spectra and near-field distributions for the antennas were simulated by DDA. DDA is an effective method for calculating the optical properties of metal nanoparticles as a result of the interaction between the nanoparticles and the incident light. The investigated antenna system consists of two identical Al nanorods. Adjacent metal nanoparticles located in close proximity to each other are referred to as dimers [22–24]. Dimers can be designed with various subwavelength structures for some applications.

In the DDA method, a metal nanoparticle with an arbitrary size and shape is approximated as an assembly of  $N$  polarizable point dipoles. When these dipoles are illuminated by the incident light, they can interact with each other. The DDA algorithm is a self-consistent solution for the polarized dipole and the near-field region. The extinction efficiency is expressed as [25,26]

$$Q_{\text{ext}} = \frac{C_{\text{ext}}}{\pi a_{\text{eff}}^2}, \quad C_{\text{ext}} = \frac{4\pi k}{|E_0|^2} \sum_{i=1}^N \text{Im}(E_{\text{loc}}^* \cdot P_i), \quad (1)$$

where  $a_{\text{eff}} = (3V/4\pi)^{1/3}$  is the effective radius. The  $E$  field enhancement distribution is expressed as [27,28]

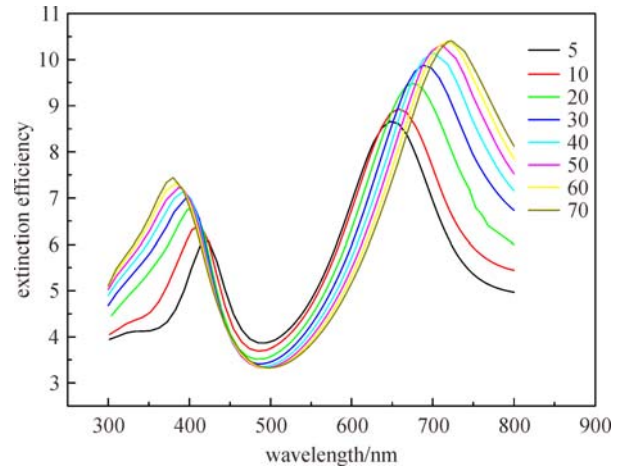
$$\gamma = \frac{|E|^2}{|E_0|^2}, \quad (2)$$

where  $|E_0|$  is the magnitude of the incident fields and  $|E|$  is the magnitude of the near-field. Simulations are performed to determine the influence of gap distance on the far- and near-field properties of a three-dimensional optical antenna in an end-to-end orientation. A three-dimensional optical antenna consists of two identical Al nanorods. Based on our previous investigation [29], the structure parameters of each nanorod were selected as follows:  $L = 126$  nm (nanorod length),  $D = 45$  nm (diameter), and varying gap distance of 5 to 70 nm. The incident direction of the excitation is along the  $x$  direction. The interdipole spacing

was fixed at 1 nm, which is in accordance with the convergence condition of the DDA method. The two Al nanorod antennas were placed in the PGMEA matrix, and the refractive index of the surrounding matrix was set to 1.4.

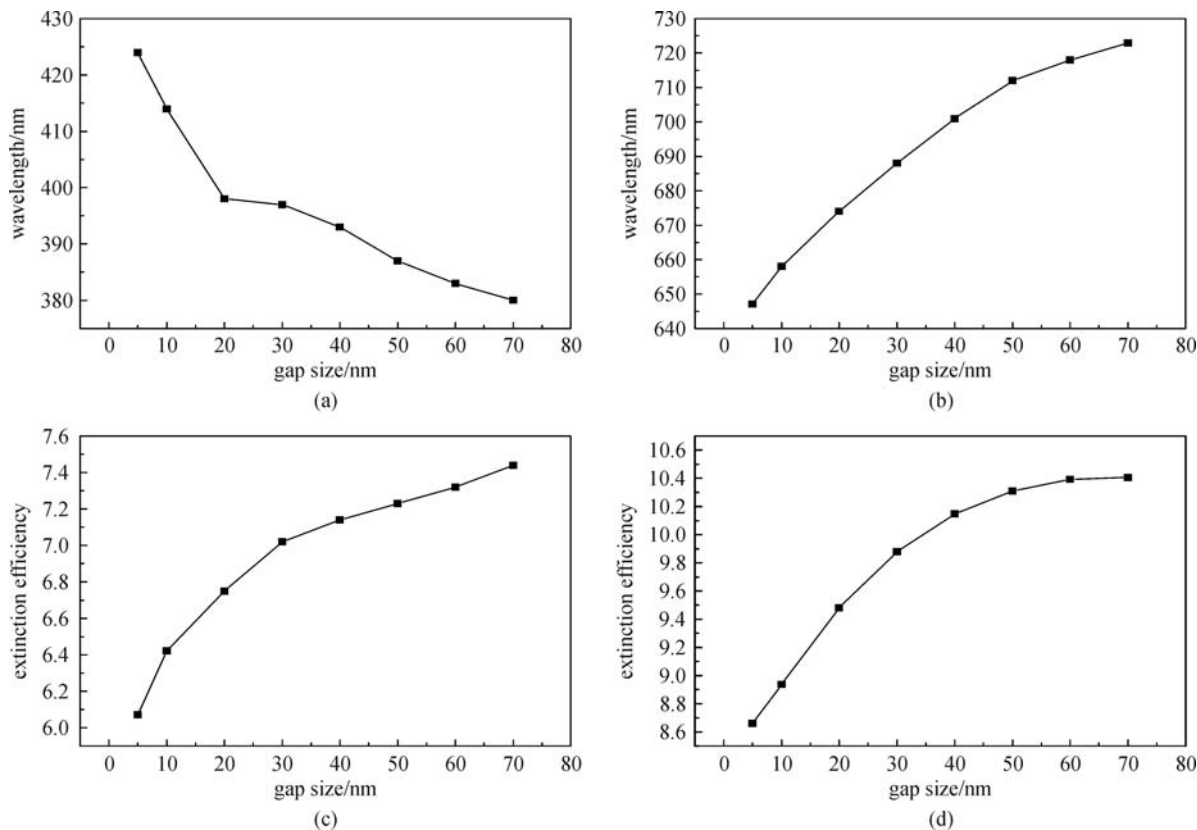
## 3 Results and discussion

Theoretical calculations of the effect of gap distance on the optical properties have been performed using the DDA method. Figure 1 plots the extinction spectra of two Al nanorod antennas with different gap distances, which vary from 5 to 70 nm. They indicate that the plasmon peak of the antenna can be changed by modulating the gap between the two nanorods. Two extinction peaks, which correspond to the longitudinal and transverse SPRs, appear in the extinction spectra. These two different SPRs, which were excited by different incident light polarizations, were attributed to the oscillations of polarized charges along the long and short axes of the nanorod, respectively.



**Fig. 1** Extinction spectra for two Al nanorod antennas with increasing gap distance from 5 to 70 nm

The effect of the end-by-end assembly on the transverse plasmon excitation is depicted in Figs. 2(a) and 2(c). The proximity of the two Al nanorods led to strong plasmon resonance coupling, which can produce hybridized plasmon modes. With the corresponding gap distance of 5, 10, and 20 nm, the transverse plasmon mode was intensely blue-shifted from 423 to 398 nm, and then slightly blue-shifted from 398 nm to 380 nm with the increasing length. The resonances in the UV were achieved because of the two Al nanorod antennas. Thus, the spectra from the UV region to the visible part can be modulated by the gap distance. When the gap distance increased, the extinction efficiency of the transverse resonance mode gradually improved as well, and the maximum value was 7.44 for  $d = 70$  nm. The results presented above demon-



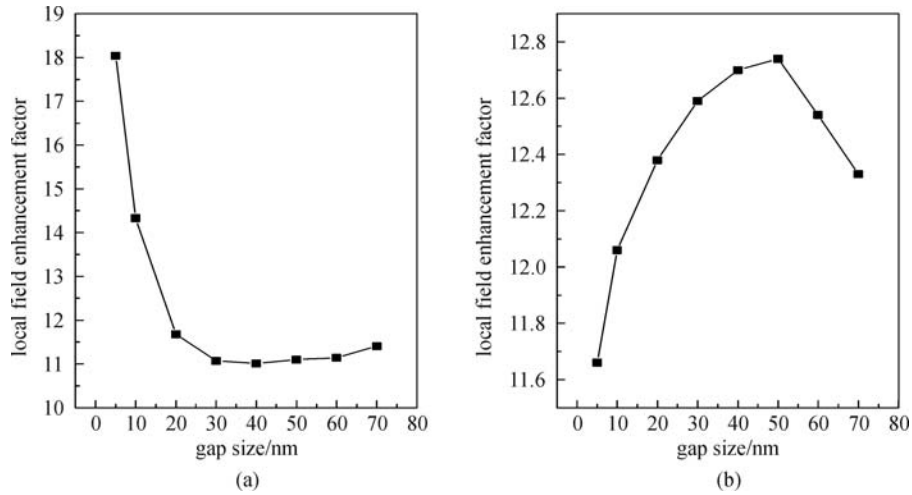
**Fig. 2** Gap effect on extinction spectra of two Al nanorod antennas: (a), (c) transverse plasmon resonance and (b), (d) longitudinal plasmon resonance

strated that tuning the plasmon peak position by varying the gap size resulted in broader and higher extinction efficiencies.

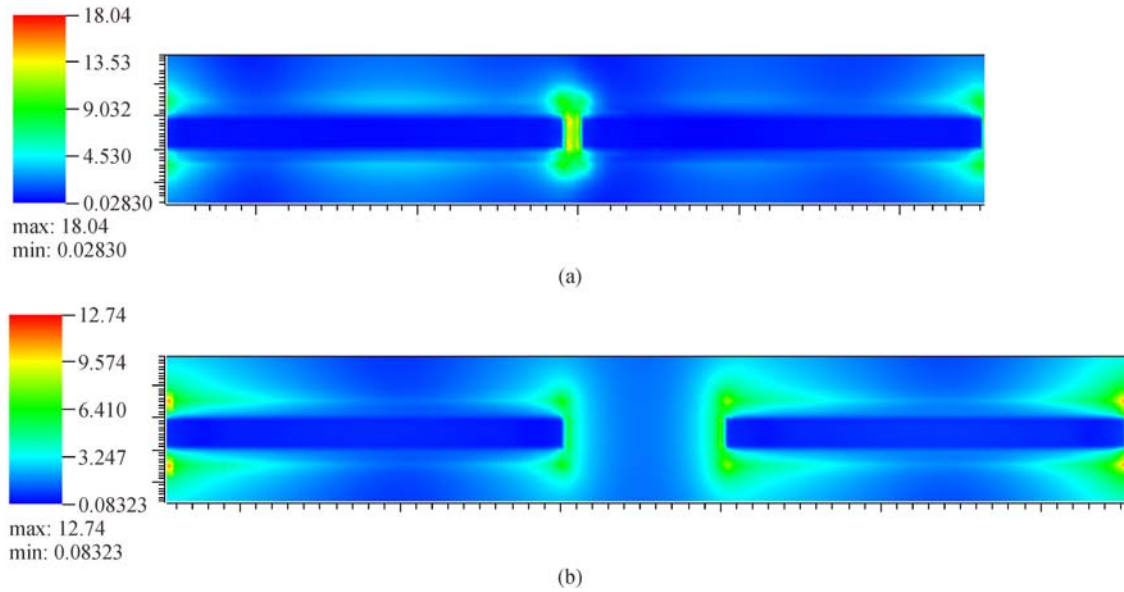
In contrast to the transverse plasmon mode, a significant red-shifted longitudinal plasmon peak exists from 647 to 723 nm with the increasing gap distance, as shown in Fig. 2(b). When the incident light was polarized along the long axis of the nanorod, the opposite types of charges were intensely distributed at the inner corners of the two Al nanorods. The coulombic attraction between the positive and negative charges in the two Al nanorods weakened the restoring force of the electron oscillation, which reduced the longitudinal SPR energy, leading to the red-shift of the resonant wavelength. This red-shift of the end-by-end assembly may be attributed to the formation of bonding atomic orbitals as a plasmon hybridization mode. However, as the gap size increased, the extinction efficiency achieve a saturation value of up to 10.3 at  $d = 70$  nm, as indicated in Fig. 2(d). Therefore, tuning the plasmon peak position by varying the gap size resulted in much higher extinction efficiencies. For the two Al nanorod antennas, the plasmon resonance can be tuned from the UV to the visible regions of the spectrum by varying the gap size. Moreover, these antennas exhibited higher extinction efficiencies in the UV and visible regions. This type of multiple resonances, which are associated with the

transverse and longitudinal plasmon resonances of the short and long axes of symmetric Al nanorods, respectively, provides great flexibility in the tunability of plasmon resonances over a large wavelength range and has some advantages in some applications, such as in the photoresist sensitivity to UV radiation and the lightning rod effect.

Plasmon near-field coupling in metal dimers can enhance the local field. Therefore, the effect of gap distance on the local field enhancement factor for two Al nanorod antennas corresponding to the two plasmon peaks was simulated. Figure 3(a) depicts the near-field distributions of the two Al nanorod antennas at the transverse resonance mode peak with different gap sizes. When the gap size increased from 5 to 30 nm, the local field enhancement factor rapidly decreased from 18.04 to 11.07. Figure 4(a) presents the simulated electromagnetic field distributions for the optical antenna with a gap distance of 5 nm at the resonant wavelength of 424 nm. When light was incident with the polarization along the short axis of the nanorod, the opposite types of charges were distributed at the lateral surface and the corner of the nanorod, which led to the “hot spots” near the midsection and the lateral side of the Al nanorod. Then, as the gap size decreased, the local electric field was enhanced not only near the midsection of the two Al nanorods, but also at the lateral



**Fig. 3** Effect of antenna gap size on local field enhancement at (a) transverse plasmon resonance and (b) longitudinal plasmon resonance



**Fig. 4** Calculated electromagnetic field distributions for the optical antenna with the gap distance of (a) 5 nm at transverse plasmon resonance and (b) 50 nm at longitudinal plasmon resonance

side of each nanorod. The positive and negative charges distributed at the upper and lower parts of the opposite end of each Al nanorod along the short axis can interact with each other. Furthermore, for gap sizes smaller than 30 nm, the local field enhancement was more sensitive to the changes in the gap size. However, for gap sizes larger than 30 nm, the enhanced factor began to be slightly affected. These results may be explained by the combination of the interaction between the charges distributed at the opposite ends and the interaction between the charges distributed at the lateral sides.

To examine how gap sizes affect the local field enhancement distributions at the longitudinal plasmon resonance, the size dependence of the near-field enhance-

ment factor for different gap distances was simulated. As shown in Fig. 3(b), the effects of gap size on local field enhancement is in accordance with a Gaussian function. When the incident light polarized along the long axis of the nanorod and illuminated the antenna of two Al nanorods aligned in an end-to-end manner, the induced positive and negative charges gathered on each nanorod's right and left ends. The positive and negative charges that were distributed on the opposite ends of the nanorod can interact with each other, which can make the local field highly localized at the surrounding area of the right and left ends of each nanorod. The larger the gap between the Al nanorods, the larger the local near-field enhancement factor is. Thus, when the gap size increased to 50 nm, the

factor reached the maximum value of 12.74 at the resonant wavelength of 712 nm, and its corresponding electromagnetic field distribution is shown in Fig. 4(b). However, the enhanced field factor decreased to 12.54 and 12.33, which corresponded to the gap sizes of 60 and 70 nm, respectively, because of the close proximity of the regions of interband transitions of the Al nanoparticles. Therefore, this reason can be regarded as a limiting factor in local field enhancement. For two Al nanorod antennas, the plasmon peak can be tuned not only by the gap size but also by the transverse and longitudinal plasmon modes. In addition, the spatial distribution of the local field can be changed under the two plasmon modes, which may provide some ideas on the utilization of two Al nanorod antennas in UV plasmonic devices.

## 4 Conclusion

In summary, because of the coupling between Al nanorods, their resonant properties and near-field distribution are more sensitive to the gap size than those of the dipole antenna. Thus, the gap size-dependent extinction spectrum and local field enhancement of the optical antenna with two Al nanorods were investigated. When the incident light is polarized along the short axis of the nanorod, the decrease in gap size leads to a distinctly blue-shift of the transverse SPR from 423 to 380 nm. Therefore, the spectra from the UV region to the visible part can be effectively modulated by the gap distance. That is, as the gap size decreases, the strong interaction between the charges that are distributed at the opposite ends and the lateral side results in an enhanced electric field. For the gap size of 5 nm, the near-field enhancement factor has the maximum value of 18.04.

In contrast to the transverse plasmon mode, a clear red-shift of the longitudinal SPR from 647 to 723 nm occurs as the gap distance increases. The coulombic attraction between the positive and negative charges of the two Al nanorods weakens the restoring force, resulting in the red-shift of the SPR wavelength. However, the enhanced near-field distributions are in accordance with the Gaussian function. When the gap distance increased to 50 nm, the local field factor reached a maximum of 12.74 at the resonant wavelength of 712 nm. In this study, the approach of the region of interband transitions of Al nanoparticles was identified as a limiting factor in local field enhancement. As a result, the gap size between two Al nanorods plays an important role in the application of the optimized properties of the optical antenna, such as near-field enhancement and SPR movement, which make the optical antenna with two Al nanorods applicable in nanophotonic and UV plasmonic devices.

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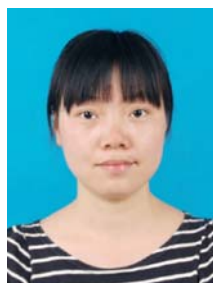
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