第 29 卷　第 12 期　　半 导 体 学 报　　Vol.29　No.12
2008 年 12 月　　JOURNAL OF SEMICONDUCTORS　　Dec.,2008

# Numerical Study of Surface Plasmons Nano-Optical Antenna and Its Array

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**Abstract**: Nano-rod and bow-tie antennas that are gold nano-antennas on dielectric material and the nano-rod antenna arrays are numerically studied by the finite difference time domain method in three dimensions. The light field that project on the antennas can be confined to a spot with subwavelength width ($\sim\lambda/11$), and the light intensity can be enhanced to 91 times the incident light in the near-field with the bow-tie antenna. The enhancement also exists in the antenna arrays. The highest enhancement of the light intensity at the bow-tie antenna gap can reach about 28000 times, and the localized field can be coupled to a nano-particle near the antenna gap.

**Key words**: near-field optics; surface plasmons; optical antenna
**EEACC**: 4110; 4120; 4145
**CLC number**: TN82　　**Document code**: A　　**Article ID**: 0253-4177(2008)12-2340-06

## 1　Introduction

Near-field scanning optical microscopy (NSOM)[1] has been applied in various fields, including biology, surface technology, material science, and data storage. However, the power transmitted from the sort of coated fiber probe with an aperture on the tip that is used in NSOM is very weak. Therefore, the fabrication of a high output power light source has been a critical issue in the progress of NSOM.

The enhanced transmission of light through subwavelength apertures and aperture arrays in metal films has attracted considerable interest[2,3]. They are explained as a phenomenon associated with surface plasmon polaritons (SPPs). However, these devices still suffer from limited output power, for the transmission is enhanced just when normalized to the aperture area.

At the meantime, there has recently been great interest in the optical properties of metallic nanoparticles and their aggregates. Such nanoparticles can induce giant local optical fields that greatly exceed the exciting fields[4,5]. Optical antennas are single or coupled metallic nanoparticles which can produce very high intensities and highly localized light fields in the optical near field optical because of the excitation of surface plasmons[6~8]. The $E$-field enhancement in apertureless near-field systems has been exploited to produce an ultra-small, ultra-intense light source. The plasmonic laser antenna that consists of a resonant optical antenna integrated on the facet of a laser diode was fabricated [9]. However the antenna fabricated in Ref.[10] consists of two nanorods. This kind of antenna exhibits field enhancement not only in the gap of the antenna but also on the far ends of the nanorods. For some applications such as optical data storage where a real single optical spot is needed, these nanorod antennas could not be used any more. This problem can be solved by employing a bow-tie design, which is demonstrated numerically in this paper.

Another major problem is that the localized enhanced field attenuates quickly. The enhancement values reach about 800 times near the middle of the gap. But the detected enhancement values in the near field are just about 9 times[9], meaning that we can get the enhanced field just within tens of nanometers. However in traditional NSOM systems, the distance from the tip of the probe to the sample is about 10～100nm. The effective distance of the enhanced field is likely too short for the application of a real device. The light field can be localized in an ultra-small area and enhanced thousands of times, and there must be some ways to get the fields out. Perhaps this problem can be solved by using bow-tie shaped aperture surrounded by concentric periodic structures in a metal film[10] or some other ways that can couple the localized field in the gap out to other structures like using a particular particle which is mentioned in this paper.

In this paper, we will numerically investigate the gold optical antennas on a dielectric layer, via three-dimensional finite difference time domain (FDTD) modeling. The field enhancement on the far ends of the antenna is reduced markedly by using the bow-tie antenna. A real single optical spot can be realized. And according to our numerical simulation results, the

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Received 29 May 2008, revised manuscript received 26 August 2008

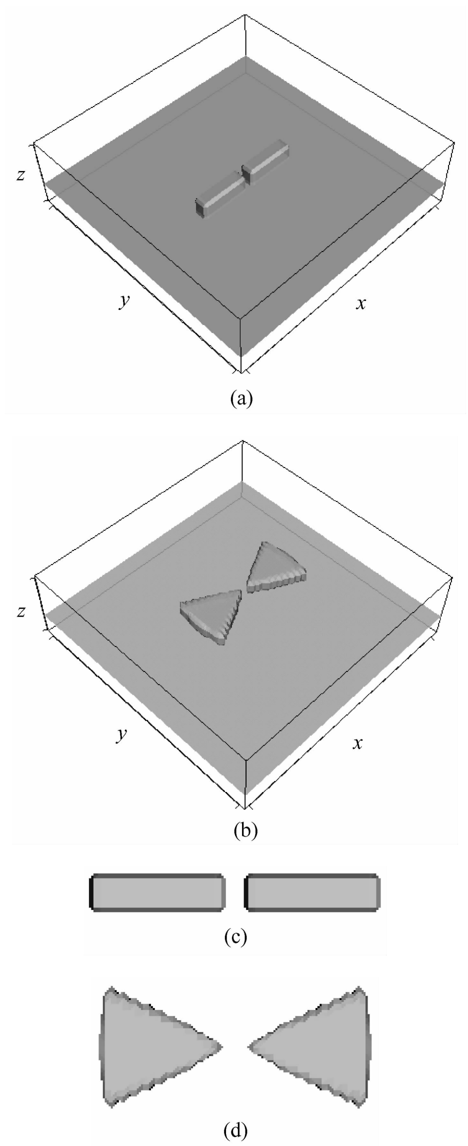


Fig. 1 Schematic of the model geometry of the nanrods (a), (c) and bow-tie (b), (d) antennas (a), (b) are the 3D images, and (c), (d) are the 2D images of the *xy* plane.

most enhancement value of the light intensity can reach about 28000 times. Such an intense field can also be used for some nonlinear effects or detection. The enhanced field is basically all confined to the tips of the antenna, and the strongly localized field can be coupled to other nano-particles again. Thus we can control the localized field and maybe use it for nano-detection or some other applications. And the antenna array is also mentioned.

## 2 Numerical model

The numerical model (see Figs. 1 (a), 1 (b)) consists of a dielectric layer ($SiO_2$) with a refractive index of 1.46 and a pair of coupled gold particles separated by a very small gap. The source is p-polarized ($H_y$, $E_x$, $E_z$) plane wave with a wavelength ($\lambda$) of 980nm introduced from the substrate side. The Drude model which is the traditional model to describe the optical properties of real metal is used in this paper:

$$\varepsilon(\omega) = \varepsilon_\infty - \frac{\omega_p^2}{\omega(\omega + 2i\nu_c)} \qquad (1)$$

Here, $\varepsilon_\infty$ is the relative permittivity at infinite frequency, $\omega_p$ is the plasma frequency, and $\nu_c$ is the collision frequency. These parameters are calculated from the measured data of the metal (in our simulation model, the values of the parameters are $\varepsilon_\infty = 14.17104$, $\omega_p = 1.472\times10^{16}$ rad/s, $\nu_c = 0.55455\times10^{14}$ Hz)[11].

Two kinds of antennas including nanorods (Fig. 1 (c)) and the bow-tie (Fig. 1(d)) are simulated in this paper. The parameters of the nanorods antenna, including length, width, height, and gap are numerically varied and optimized. In the simulation process, the length ($l$) of the antenna arm was varied from 50 to 300nm in 10nm steps. For each value of $l$, the height ($h$) of antenna was varied from 20 to 300nm in 10nm steps. The width ($w$) antenna was varied within the length ($l$). The gap was varied from 20 to 100nm in 10nm steps. Note that p-polarized light is needed to excite SPPs in the antenna structures in this paper. The direction of the $E$ field must be parallel to the antenna along the $x$ direction. In all cases, the dielectric material above the metal nanoparticles is air and below it is $SiO_2$. The simulation region size is $1\mu m \times 1\mu m \times 1\mu m$, with a uniform cell of $\Delta x = \Delta y = \Delta z =$ 5nm. Around the simulation region is a perfectly matched layer absorber. Through changing the parameters of the antennas, we can find the optimized parameters that can localize and enhance the incident light field most effectively. After numerical optimization, the parameters of the nanorods antenna, respectively, are chosen as follows: arm length ($l$), 180nm; width ($w$), 40nm; height ($h$), 50nm; gap, 40nm. The parameters of the bow-tie antenna, including length, height, and gap are chosen as the same as the nanorods antenna. The bottom width of the bow-tie antenna in the $y$ direction is changed from 50 to 300nm in 10nm steps and chosen as 200nm at last.

The $E$ energy intensity distribution of the nanorods antenna and bow-tie antenna are shown in Fig. 2. First, let us see the results of the nanorods antenna. The $E$ energy intensity distribution of the $z$-cut plane at $z = 25$nm where is the middle of the antenna in the $z$ direction is shown in Fig. 2(a). It can be seen that the enhanced field is basically localized at the tip of the antenna and the highest value in the gap reaches about 11000 times of the incident $E$ intensity. However the enhanced field attenuates quickly. In the plane that just above the antenna 20nm at $z = 70$nm, the enhancement of the field has declined to 43 times

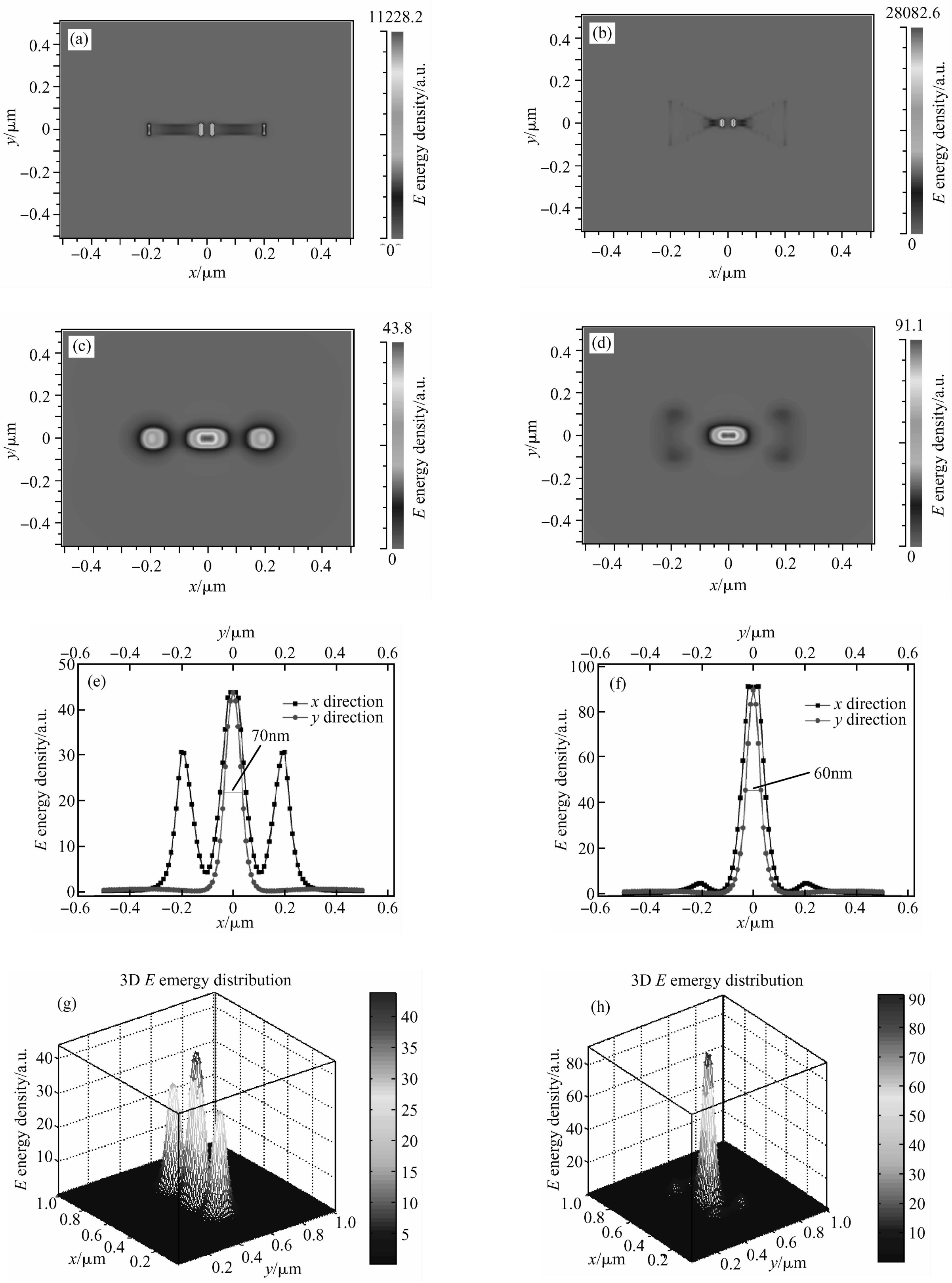


Fig. 2 Distribution of the $E$ energy density and the spot size of the nanorods antenna (a), (c), (e), (g) and bow-tie antenna (b), (d), (f), (h) The simulation region size is $1\mu m \times 1\mu m \times 1\mu m$, with an uniform cell of $\Delta x = \Delta y = \Delta z = 5nm$. (a), (b) are at the middle of the antenna in the $z$ direction at $z = 25nm$, and (c), (d) are at 20nm above the antenna at $z = 70nm$. (e), (f) represent the $x$-cut and $y$-cut plane of the antenna, respectively. The black line and gray line represent the $x$ direction and $y$ direction, respectively. (g), (h) are the 3D image of (c), (d), respectively.

(Fig. 2(c)). And the enhanced field at the far ends of the nanorods also reaches about 30 times. In Fig. 2(e), the black and gray lines represent the $x$-cut and $y$-cut plane of the antenna, respectively. We can see three peaks along the antenna in the $x$ direction. The lateral full width at half maximum (FWHM) of the central peak of the near-field intensity distribution is 100nm in the $x$ direction and 70nm in the $y$ direction. Figure 2(g) shows the 3D image of the plane at $z$ = 70nm to illustrate the energy distribution clearly. Therefore we can understand that it will be very difficult to use this kind of antenna as a light source where a single optical spot is needed. The bow-tie antenna can solve this problem effectively (Fig. 2(f) and Fig. 2(h)). The enhanced fields at the gap can reach about 28000 times at $z$ = 25nm (Fig. 2(b)) and 91 times at $z$ = 70nm (Fig. 2(d)) which is two times the nanorods antenna. The lateral full width at half maximum (FWHM) of the central peak of the near-field intensity distribution is 90nm in the $x$ direction and 60nm in the $y$ direction that are all smaller than the nanorods antenna. This intense optical spot whose width is about equal to $\sim\lambda/11$ is localized within an area that is much smaller than what we would obtain with conventional optics such as lenses (Rayleigh limit). And the intensity of the localized spot can reach about 91 times the exciting fields in the optical near field. Hence with the bow-tie antenna, we can get a real single optical spot that is stronger and more localized than the nanorods antenna.

## 3 Coupling out the localized light field

The above numerical simulation results show that the localized enhanced field can reach about to 28000 times of the incident light intensity at the tip of the bow-tie antenna. However the enhanced field attenuates quickly and decreases to 91 times just 20nm above the antenna. In this section, we will introduce a nanoparticle with the same material of the antenna to couple with the enhanced field which is localized in the gap of the antenna (Fig. 3(a)). The particle which is like a column with a height of 100nm in $z$ direction localized at (0.08, 0, 0.05$\mu$m) has two sharp tips and its diameter at the centre ($z$ = 0.1$\mu$m) is 60nm. According to the author's study, this kind of nano-structure is the most effective coupling shape. Maybe, there is some more effective way to couple the localized field that need to be further investigated, and the physical origin and theory also need to be further studied.

This particle mainly coupled with the field localized at the antenna arm where it is positioned as

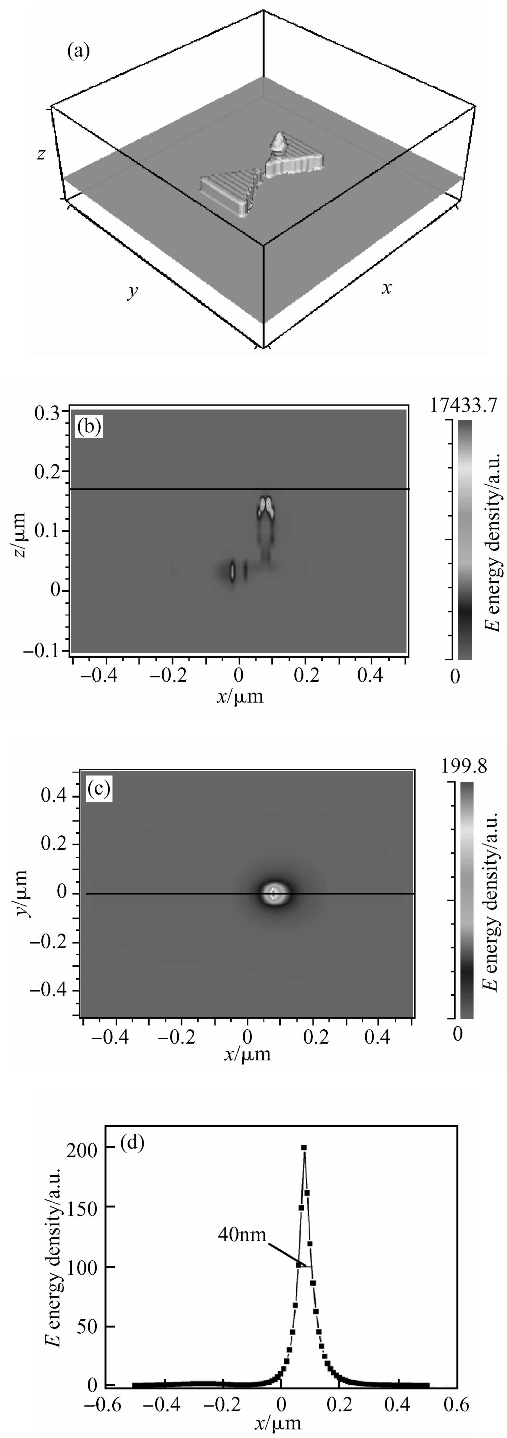


Fig.3 Schematic of the model geometry of the bow-tie antenna with an introduced particle (a), the distribution of the $E$ energy density at $xz$ plane (b) and $xy$ plane (c), and the spot size of the enhanced field at the particle tip (d) The simulation region size is 1$\mu$m×1$\mu$m×1$\mu$m, with an uniform cell of $\Delta x = \Delta y = \Delta z$ = 5nm.

shown in Fig. 3(b). The enhanced field in the gap has declined. Especially for the arm where the particle is located, the enhanced field declined more remarkably. The strongest light intensity is not in the gap of the antenna any more, but at the tip of the introduced particle. Most of the enhanced light field that local-

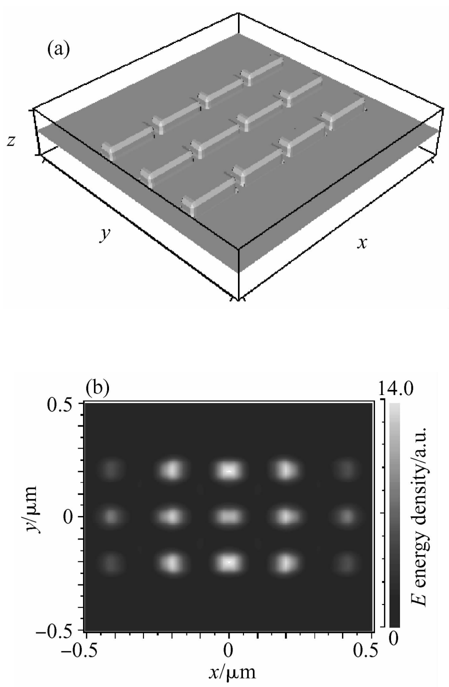


Fig. 4 Schematic of the model geometry of the antenna array (a) and the distribution of the $E$ energy density at $xy$ plane (b) The simulation region size is $1\mu m \times 1\mu m \times 1\mu m$, with an uniform cell of $\Delta x = \Delta y = \Delta z = 5nm$.

ized in the gap before is coupled to the particle. The most enhancement of the light field at the tip of the introduced particle reaches about 17,433 times of the incident intensity and also attenuates quickly. Figure 3 (c) shows the $xy$ plane where $z = 0.17\mu m$ following the black line as shown in Fig. 3(b). We can see that the enhanced field decline to ~200 times just at 20nm above the particle tip. However this has been better than the nanorods or bow-tie antennas that are simulated above. The attenuated rate is lower than the bowtie antenna. The effective distance of the enhanced field has been extended. Figure 3(d) shows the light intensity distribution along $x$ axis following the black line in Fig. 3(c) where $y = 0\mu m$. The peak value is corresponded to the tip of the particle at $x = 0.08\mu m$ just where the particle is localized. And the FWHM of the spot width is about 40nm. Thus it can be demonstrated that the coupling between the antenna and the introduced nanoparticle is truly exist and effective. It means that the intense field localized in the gap of the antenna can be coupled out. The problem of the effective distance of the enhanced field may be solved in this way in the future. And this mechanism can also be used to detect some special nanoparticles or to excite some special effects like nonlinear phenomenon.

## 4 Antenna arrays

In this section, nanorods antenna array is discussed. Figure 4(a) shows the schematic model geometry. There are 4 arms in the $x$ direction. The arm length ($l$) is 180nm, width ($w$) is 40nm, height ($h$) is 50nm, and the gap is 40nm as optimized above. In the array, there are 9 gaps between the antenna arms. And Figure 4(b) shows the distribution of the optical intensity at 20nm above the antenna array. It can be seen that the optical fields are effectively localized and enhanced at the antenna gaps. The enhancement of the light field can reach about 14 times at all of the gaps. Hence we can conclude that, if the antenna is arranged as an array, the enhanced fields can be attained at several points. That means, with such kind of array, we can confine and enhance the incident light field into many nano-sites (40nm) that will be useful for the nano-etching. And also, the antenna array can absorb the incident light effectively, at least, the reflection can be largely reduced, that will be useful for some detectors or solar cells.

## 5 Conclusion

We have designed two kinds of Au nano-antennas on a dielectric layer ($SiO_2$) and the bow-tie antenna can confine and enhance the light field better than the nanorods antenna. With the bow-tie antenna, we can get a real single optical spot that will be easily used as a near-field source. The size of the spot in the near field can reach about 90nm × 60nm which lateral size is only about 1/11 times the wavelength of the incident light, and high resolution can be expected if this bow-tie antenna is used as a SNOM tip. FDTD numerical simulation results also show that the localized field in the gap of the bow-tie antenna can be enhanced to 28000 times the incident light intensity. Although the enhanced field attenuates quickly and decreases to 91 times at just 20nm above the antenna, it is still much stronger than the transmission intensity from the normal nanohole or some modulated nanoholes via surface plasmons. In addition, the enhanced field can be coupled to some other particles effectively. It can be used to extend the effective range of the enhanced field or to detect special nanoparticles. And the enhanced effects also exist in antenna arrays which can be used to enhance the optical absorbability or sensitivity of detection. Such devices and systems will be useful tools for future research in nano-scale biology, integrated optics, and nano-lithography.

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# 模拟分析具有表面等离子体效应的纳米光学天线及其阵列


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**摘要:** 基于时域有限差分方法,模拟分析了位于介质材料上的杆形和蝴蝶结形两种金纳米天线及杆形天线阵列.结果表明天线近场光斑直径约可以达到波长的 1/11,蝴蝶结形天线的光斑强度可以比入射光场增强 91 倍.杆形天线阵列仍可以实现这种增强效应.蝴蝶结形天线中光场增强最高可以达到 28000 倍,而且局域化的光场可以耦合到天线臂上的纳米颗粒.



**关键词:** 近场光学; 表面等离子体; 光学天线

**EEACC:** 4110; 4120; 4145

**中图分类号:** TN82 **文献标识码:** A **文章编号:** 0253-4177(2008)12-2340-06



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2008-05-29 收到, 2008-08-26 定稿