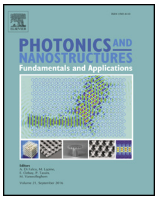
Photonics and Nanostructures – Fundamentals and Applications 25 (2017) 72–76

Contents lists available at ScienceDirect

Photonics and Nanostructures – Fundamentals and Applications

journal homepage: www.elsevier.com/locate/photonics



# Engineering two-wire optical antennas for near field enhancement

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ARTICLE INFO

*Article history:*
Received 21 December 2016
Received in revised form 14 March 2017
Accepted 19 March 2017

*Keywords:*
Optical antenna
Surface plasmon resonance
Field enhancement
Nanowire

ABSTRACT

We study the optimization of near field enhancement in the two-wire optical antenna system. By varying the nanowire sizes we obtain the optimized side-length (width and height) for the maximum field enhancement with a given gap size. The optimized side-length applies to a broadband range ($\lambda = 650–1000$ nm). The ratio of extinction cross section to field concentration size is found to be closely related to the field enhancement behavior. We also investigate two experimentally feasible cases which are antennas on glass substrate and mirror, and find that the optimized side-length also applies to these systems. It is also found that the optimized side-length shows a tendency of increasing with the gap size. Our results could find applications in field-enhanced spectroscopies.

## 1. Introduction

Plasmonic nanostructures can concentrate light energy into nanometer scale [1] due to the surface plasmon resonances (SPRs). The strong resonance responses and high field concentration can give rise to large near field enhancement (NFE) around the structures [2–4]. This feature enables many applications such as surface-enhanced Raman scattering (SERS) [5,6], emitter fluorescence and emission[7–11], and nonlinear optics [12–15]. It is known that the position and strength of SPRs show complex variations with structure shape, size and surrounding environment. This property provides large adjustability for NFE but also makes the optimization of geometric parameters for NFE not so intuitive. Thus, many efforts have been devoted to investigating the NFE properties in different nanostructures. This kind of structure is also called optical antenna [16–18] which is an analogue of the classical radio-frequency (RF) antenna. Lots of optical antennas with different patterns have been proposed to obtain efficient NFE. These patterns include single nanorods [17,19,20], two-wire antennas [21–26], Bow-tie antennas [7,27–31], spheres antennas[32,33], nanotube antennas [34], cross antennas [35], split-ring antennas [36,37], T-shaped antennas [38] and Fan-shaped antennas [39]. While different patterns have been proposed, the optimization of the geometric sizes within one pattern for the NFE is also important and plays a fundamental role in the comparison between these different patterns for the NFE performance.

The two-wire optical antenna consists of two nanowires which are end-to-end aligned with a narrow gap [17]. Generally, there is a dipolar SPR mode one each nanowire. The two dipolar modes will form a bonding hybridization mode through the strong in-phase coupling, which can create strong NFE inside the gap at resonance. This kind of antenna has been widely investigated due to the fact that the structures are simple and can be easily fabricated in experiments. It has been widely realized that the gap size and wire length can greatly affect the NFE spectrum including both the peak value and position [40]. The NFE generally increases and the resonance position redshifts with decreasing the gap size (or increasing the wire length) of this antenna. It should also been noted that engineering the NFE in the antenna structures with given gaps and wavelengths is also very important, especially for some applications, for example, the fluorescence enhancement [8]. To achieve strong enough fluorescence, there should be certain distance between the emitter and antenna to avoid quenching. The antenna resonance wavelength should match the absorption of emitters to enable the strong excitation. So, the realization of strong enough NFE for a given gap size and working wavelength is required for this kind of application. The optimization of antennas for the NFE with given gaps and wavelengths can be carried out by considering the effects from the nanowire width and height. However, this kind of optimization has not been studied thoroughly.

Here we investigate the engineering of the nanowire lateral size for NFE in the two-wire antennas with given gap sizes. We start with a given wavelength and gap size, and the antennas are in vacuum. The optimized side-length (width and height) can be obtained, which is found to be closely related to the ratio of extinction cross section to the field concentration size in the gap. It is seen

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http://dx.doi.org/10.1016/j.photonics.2017.03.007

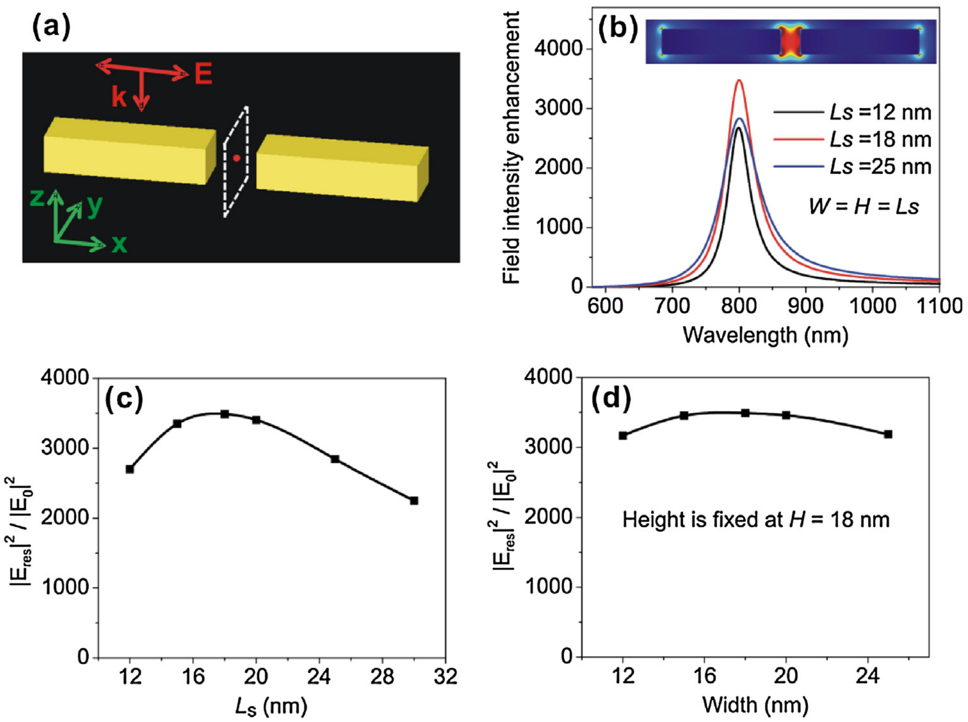

**Fig. 1.** Optimized geometric size for NFE at $\lambda = 800$ nm. The gap size is fixed at 15 nm. (a) Schematic of the investigated two-wire antenna system. (b) Field intensity enhancement ($|E|^2/|E_0|^2$) spectra at the gap center point with the side-length $L_s = 12$, 18 and 25 nm and the corresponding resonant wire length $L = 67$, 91 and 107 nm, respectively. (c) The resonant $|E|^2/|E_0|^2$ ($|E_{res}|^2/|E_0|^2$) at $\lambda = 800$ nm as a function of side-length ($L_s$). For each $L_s$, the rod length is chosen that the resonance is at $\lambda = 800$ nm (the wire lengths for $L_s = 12$, 15, 18, 20 and 25 nm are 67, 79, 89, 95 and 107 nm, respectively). (d) $|E_{res}|^2/|E_0|^2$ at $\lambda = 800$ nm as a function of width $W$ with the given height $H = 18$ nm.

that the NFE values vary significantly with different side-length although the antennas are all resonant at the same wavelength and have the same gap size. The optimized wire side-length also applies to a broadband range under consideration ($\lambda = 650$–1000 nm). We also try some other experimentally feasible configurations, namely antennas on glass substrate and with mirror. It is found that the optimized side-length still applies there. The gap effects on the optimized size-length for NFE are also considered. The optimized side-length shows a tendency of increasing with gap size. Our results demonstrate the limit of NFE in the basic two-wire antennas, which could serve as a baseline for the design of more complex NFE-based antennas.

## 2. Results and discussion

Fig. 1(a) shows the schematic of the antenna structure. The system is excited by a plane wave with polarization along the two nanowires. The geometric size of each nanowire is the same. Au is taken as the material with dielectric constants taken from Palik's book [41]. Here we choose a gap size $d = 15$ nm and a working wavelength $\lambda = 800$ nm to carry out the optimization of antennas for the NFE. The antennas are in vacuum. The calculations are done by using a commercial finite-difference time-domain (FDTD) software (FDTD Solutions). The electric field at the center point of the gap is calculated to characterize the NFE property of the two-wire antennas. It is easy to verify that for an antenna with a given width ($W$) and height ($H$), the maximum field enhancement occurs at the wire length where the resonance position of the antenna matches the working wavelength.

Fig. 1(b) shows the field intensity enhancement ($|E|^2/|E_0|^2$) spectra at the gap center with different nanowire side-lengths ($W$, $H$). Here the width and height of the nanowires are the same ($W = H$), and they are denoted by $L_s$. The longitudinal lengths of the nanowires are chosen that the antenna resonances are all at about $\lambda = 800$ nm. On each nanowire, the resonance is a dipolar surface plasmon mode (see the inset in Fig. 1(b). On the $|E|^2/|E_0|^2$ spectra, each resonance peak value corresponds to the maximum $|E|^2/|E_0|^2$ ($|E_{res}|^2/|E_0|^2$) for the given $L_s$ (the corresponding wire length is unique with given gap size and working wavelength). It is seen that $|E_{res}|^2/|E_0|^2$ varies with $L_s$. Fig. 1(c) shows the $|E_{res}|^2/|E_0|^2$ as a function of $L_s$. The $|E_{res}|^2/|E_0|^2$ shows a peak value near $L_s = 18$ nm. This $L_s$ is the optimized size to get the maximum $|E_{res}|^2/|E_0|^2$ (written as $|E_{max}|^2/|E_0|^2$) of the two-wire antenna system at $\lambda = 800$ nm.

In the above discussion, we have chosen nanowires with $W = H$. Now let us see the case with different $W$ and $H$. To illustrate this, we fix the height $H$ at the optimized value $H = 18$ nm and change the width $W$. For each width $W$ one can extract the $|E_{res}|^2/|E_0|^2$ at $\lambda = 800$ nm as shown in Fig. 1(d). The field enhancement decreases when the $W$ value goes away from $H$. So the NFE cannot be further optimized by tuning the ratio of $W$ to $H$. Due to this fact, we will keep using the same $W$ and $H$ ($L_s$ $W = H$) in the following discussion.

To get more physical insight into the optimization of the side-length for NFE, we now turn to the energy conversion (or light extinction) and field concentration properties in our system. As it has been pointed out that the $|E|^2/|E_0|^2$ at high NFE region of an optical antenna cavity can be expressed as [2] $|E|^2/|E_0|^2 = \gamma_{rad}A_cQ^2/\left(4\pi^2c^2\eta\varepsilon_0\lambda_0V_{eff}\right)$ where $\gamma_{rad}$ is the energy decay rate due to radiation, $A_c$ is an effective radiation cross section of the resonant cavity mode, $Q$ is the total quality factor of the antenna, $\eta$ is the impedance of free space, $V_{eff}$ is the effective mode of the antenna, $c$ and $\lambda_0$ are the speed and wavelength of light, respectively. Here $\gamma_{rad}A_cQ^2$ represents the ability of energy conversion (or light extinction) by the antenna at resonant wavelength, and $V_{eff}$ is related to the near field concentration around the antenna. In our system the gap distance is fixed, so the field concentration property can be illustrated by the cross section field distribution pattern. With the field intensity distribution on the cross section (Fig. 2(a)), one can get the full width at half maximum (FWHM) size