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Ultracompact Surface Plasmon Polariton Beam Focusing with Metal-Coated Nanoshell Structures

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In this paper, we report on beam focusing and on directing of surface plasmon polaritons (SPPs) with metal-coated nanoshell chain structures. Using nanoshells enhances the interaction between particles and leads to much higher field intensities in the focal point. Beam focusing has been realized over a wide wavelength range, due to the inherent large tuneablity of the plasmon resonance in the underlying nanoshells. The focusing device topologies proposed here are easy to adapt to long wavelength operations. Finally, a simplified metallic strip structure was proposed to explain the broadband characteristics of the chain structures as well as to compare and to verify its proper design.

Keywords: Numerical Modelling, Surface Plasmon Polaritions, Focusing, Nanoshell Structures.

1. INTRODUCTION

Surface plasmon polaritons (SPPs) are collective electron oscillations bound to the interface between metal and dielectric, due to the interaction of the light field with conducting electrons in metal.[1] The particular dispersion characteristics of SPPs enables the confinement of light into the nanoscale, and hence providing further measures for the miniaturization of functional optical devices while enhancing their functional density virtually by orders of magnitude.[1] During past decades SPP-based applications have been demonstrated for biosensing, modulators, and switches, as well as for highly integrated optical devices.[1–4] Here, we aim at the design of SPP focusing devices, which are capable of realizing sub-wavelength light confinement, as well as far field to near field conversion on a planar structure. Several structures for SPPs focusing have been proposed, i.e., circular and elliptical slits milled into silver and aluminum thin films,[5] hole-arrays machined into thick silver films.[6] In addition, SPPs have also been localized at the narrow end of a tapered plasmonic rib waveguide,[7] and in correspondingly shaped composite metal–dielectric–metal structures.[8] More recently, focusing devices, like the curved chains of nanoparticles located on a metal surface have been investigated experimentally and theoretically.[9–10] In this paper, we propose another focusing device topology with nanoshell chains located on a substrate that supports surface waves such as e.g., SPPs. One of the promising features of nanoshells we used here for SPP focusing is that large field enhancement can be obtained, due to strong light field interactions (originating from modes hybridization on the metal–dielectric interfaces) in the particular shell structures.[11] This increases the scattering cross section (SCS) of the particle chain and thus, larger field intensity is expected at focal point with the help of a correspondingly tailored scattering field, stemming from the interacting SPPs of the chain structure.

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2. MODELLING

In our work we demonstrate numerically the diffractive focusing from SPPs in nanoshell chains using the Finite Element Method. Here for simplicity reasons, we set up a two dimensional (2D) model, where the circular nanoshell consists of a silica core (radius $r_1 =$ 10 nm) with a refractive index of 1.5, which is coated with a metallic layer (silver) of thickness $r_2 - r_1 = 10$ nm. The overall focusing structure is embedded in air and depicted in Figure 1(a). Typically, it represents a two-layer V-shaped nanoshell chain having identical center-to-center distances of $d_c = 50$ nm. The full angle between the two branches is selected as 60°. This choice is only based on the topology considerations of the structure where the elliptically arranged chains are correspondingly replaced by the straight chains. Note that a focusing structure based on elliptically arranged metallic particles have been presented in Ref. [10]. The second V-shaped chain is just a

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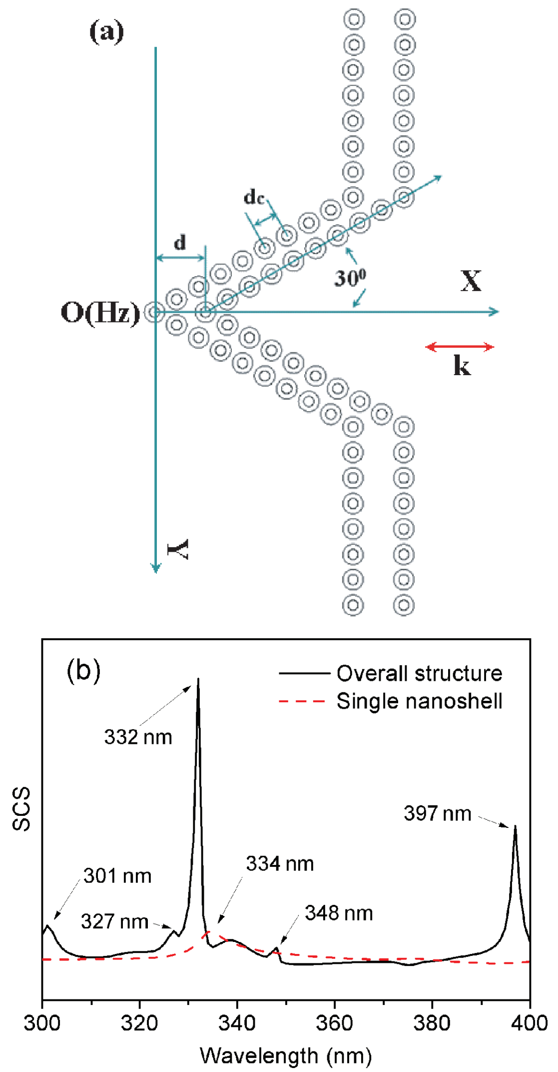

Fig. 1. (a) Schematics of the focusing device topology; (b) Computed spectral responses of the overall device's scattering cross-section (SCS) and a single nanosehell. The wavelength peaks (indicated by arrows) are assigned to resonance conditions associated with electric fields that are strongly enhanced at the various particles' surface.

copy of the first one that has undergone a shift along the x-direction of $d = 100$ nm. Referring to this topology, the V-shaped part of our focusing structure could be viewed as a "broadband version" of a half ellipse, where the curved part of the ellipse is replaced by two corresponding straight chains. The two "winglets" adjacent to the truncated V-part act as a matching structure with respect to the (incident) radiation field. This is tantamount to minimizing the beam divergence in the radiation characteristics, which is caused by the truncation of the V-part and, hence, revealing the impedance mismatch.

Since the SPP waves are transversely polarized, the H-field has only a z-component as indicated in Figure 1(a). In the numerical simulations we consider a light beam within the wavelength range of 300–400 nm that is incident on the V-type chain structure. It's worth mentioning that the resonances of the single nanoshell should not be necessarily all included in this wavelength range. However, because of the large wavelength tunability of the underlying nanoshells,[11] particular resonances can be easily tuned to longer wavelengths. For example, a simple reduction of the shell thickness $r_2 - r_1$ to 5 nm would lead to a resonance shift about 200 nm (i.e., when $r_1 = 15$ nm, $r_2 = 20$ nm). To provide a comprehensive picture for the structure's resonances, the spectral response of the scattering cross section (SCS) of both, the overall focusing device and the single nanoshell have been calculated as displayed Figure 1(b). Here, the wavelength peaks are assigned to resonance conditions associated with electric fields that are strongly enhanced at the various particle's surface, as indicated by arrows in Figure 1(b).

3. RESULTS AND DISCUSSION

Figure 2(a) shows the intensity distribution of the proposed focusing device at the wavelength of 327 nm, which is one of the resonant wavelengths of the overall structure as indicated in Figure 1(b), where the focusing behavior is pronounced. The overall structure is excited by a plane wave (Hz) incident from the $+x$-direction. Focusing behavior is actually observed for a wavelength range between 310 nm and 335 nm. The field enhancement factor in the focal point can reach values up to 40 even for non-resonant operation wavelengths, such as 330 nm. Larger field enhancement can be found within the structure but not at the focal region, namely not at the tip of the V-type chain. The field enhancement factor is defined as the ratio of the maximal electrical field strength (in the focal area) to the field strength of the incident wave. However, the spot size of the focal point is wavelength dependent, and the smallest spot size is found for wavelengths approaching the plasmon resonance of the single nanoshell (i.e., 334 nm). The resulting Full-Widths at Half Maximum (FWHM) of the spot size in y-direction (cf. Fig. 2(c)) amount to 59 nm, 51 nm, and 52 nm for the corresponding operating wavelengths at 330 nm, 332 nm, and 334 nm, respectively. These FWHM values are much less than half of operating wavelengths. Therefore, subwavlength focusing can be realized in the structure. Smaller FWHMs are obtained if the field intensity is sampled along the surface of the outmost-left nanoshell, provided the strongest field is located on the outer surface of nanoshell (this is realized by optimizing the nanoshell geometries). Hence, the spot size is closely related to the size of the nanoshell. This has been verified while inspecting the field intensity of the focal spot along the x-direction revealing an exponential decay due to the SPP fields, as shown in Figure 2(d). For other wavelengths that are not displayed here (i.e., from 310 nm to 335 nm), focusing is obtained with FWHMs less than half of incident wavelength as well, showing the main advantages of using nanoshell structures compared to regular optics.

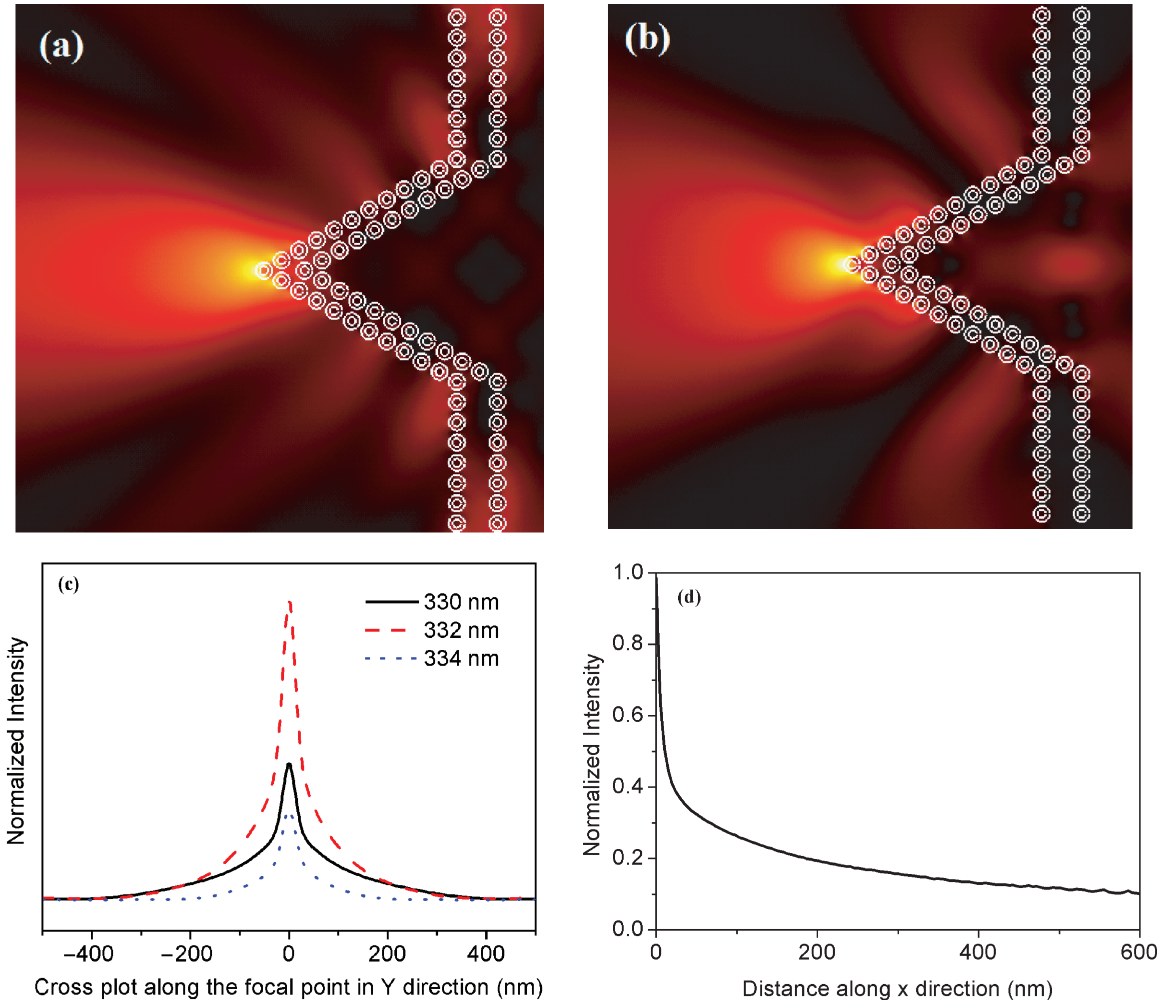

Fig. 2. Simulated field intensity distribution of the focusing V-shaped nanoshell chain (a) at 327 nm for plane wave excitation from the right; (b) at 334 nm; (c) Intensity profiles transverse to the focal area adjacent to the outmost nanoshell for different wavelengths. For clarity reasons, the data for 330 nm was enlarged 10 times, and the data for 334 nm was enlarged 50 times; (d) Intensity profiles along x-direction at a wavelength of 334 nm, the starting point is at the outmost nanoshell.

From the results shown in Figures 2(a–c), one can observe that the location and the intensity of the focus are both wavelength dependent. This arises from the different mode patterns in the nanoshell at different wavelengths, where the plasmons on the two metallic–dielectric interfaces are hybridized. Such hybridized modes are typically different from those dipole modes in the hole-array structure.[6] At the proper resonance of the single nanoshell (334 nm, Fig. 2(b)), one can see an additional focal point on the right hand side of the structure, with a much lower field enhancement factor of about 5 and an increased FWHM of 140 nm. This undesired focal point on the right hand side of the structure is also present at some wavelengths in the structure and it is essentially the results of interference effects between the hybridized modes and the reflected waves with the incident light. Due to the fact that the field concentration in the structure strongly depends on the operating wavelengths as well as on the geometric parameters of the structure, optimizing the structure can impede the unwanted interference pattern and therefore the focusing can be further improved. For instance, by adjusting the interparticle distance, mode coupling between two adjacent nanoshells can be effectively tailored. As mentioned before the field concentration at some resonant wavelengths can be located somewhere in the chain instead of around the V-tip. As a consequence, the focusing behavior such as e.g., revealed from Figures 2(a–b) will not be observed in this case, which is understandable from the aforementioned reasons.

The focusing structure also applies for the reverse direction, where the plane wave excitation is from the left ($-x$). As conjectured from the aforementioned elliptical chain structure[9, 10] with light focusing appearing in the half ellipse's focal point, our V-shaped chain provides a bright focal spot on the right hand side of the structure (not shown here for brevity). However, the wavelength bandwidth (5 nm) for focusing operation is smaller compared to the prior case of right ($+x$) incidence (25 nm), and strong focusing is only obtained for wavelengths close to the resonance at 334 nm of the single nanoshell. The field intensity in the focal region (not shown here) provides a field enhancement factor of 6 at the operating wavelength of 334 nm, which is less than the value obtained in the previous case (Fig. 2(a)). The lateral FWHM of the focal region amounts to 180 nm for the case of left incidence and is therefore larger than in the previous case of right incidence.

For simplification (and verification) purposes our focusing chain structure can be evolved into a much simpler coated strip topology having the same layout as the chain arrays. Here, the overall particle chain was replaced by three V-shaped strips, one consists of a dielectric layer with thickness 20 nm (corresponding to the nanoshell core) sandwiched by two 10 nm thick metallic layers (representing the metallic coating of the nanoshell). The spectral responses and the field distribution for such equivalent strip structures at an operation wavelength of 326 nm are depicted in Figures 3(a)–(c), respectively. The intensity distribution around the strip structure (Fig. 3(b)) already reveals the characteristics of the focusing particle chain from Figure 2(a) whereas the doubled strip structure (Fig. 3(c)) shows a nearly identical behavior, i.e., a FWHM with a difference of only 8 nm is obtained at the same wavelength. The intensity in the focal point is slightly different compared to the nanoshell chain, i.e., 1.2 times smaller than the case shown in Figure 2(a) when it operates at a wavelength of 326 nm. Compared to the nanoshell chain, the resonances of the given V-shaped strip were red-shifted by 1–7 nm as well as the corresponding focusing wavelengths. These differences arise from the structural variations between these two structures (namely the different geometries), which originate from the different coupling mechanism within the structure. For instance, the focusing behavior of the nanoshell chain is merely realized by the near-field coupling of adjacent nanoshell modes, while the focusing of the strip is mainly based on the interference of surface waves in the strip. Similar behaviors for the equivalent strip structures are found when the light is incident from left-hand side, including a slight beam divergence, which also exists for the corresponding nanoshell chain structure. Like in the nanoshell chain, the spot size of the focus in the coated strip structure can be tailored as well, by changing the strip size or the full angle of the V-shaped strips. It's worth noting that an increase of the strip number will enable coherent back reflection while narrowing the operation bandwidth of the focusing device.

We have to mention that although our work is in 2D, it is feasible to extend the structure into three dimensions (3D), because such nanoshell structures have been fabricated via chemical methods by Halas et al.[11] several years ago, and various related applications have already been proposed[12] and experimentally verified[13] based on such 3D nanoshell structures. Since the nanoshell structures provide more

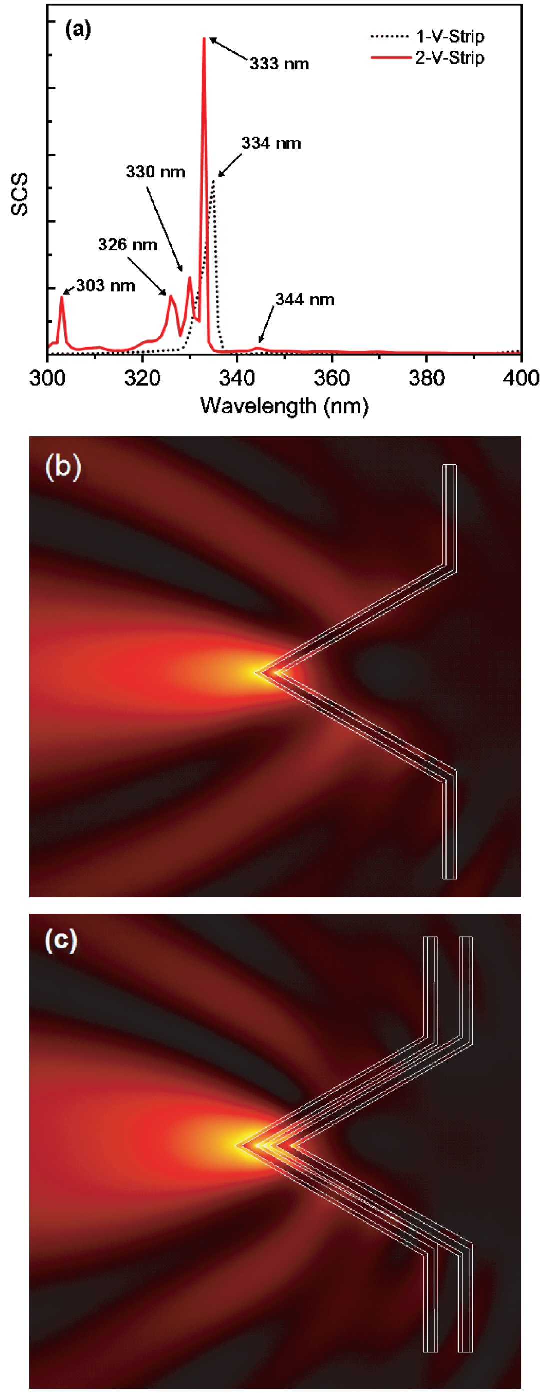

Fig. 3. (a) Spectral responses for the equivalent strip structures. The resonances are indicated by arrows in the figure. (b) and (c): Simulated field intensity distribution of the equivalent strip structures for plane wave excitation from the right: (b) The equivalent structure corresponding to a single V-type nanoshell chain at an operating wavelength of 326 nm; and (c) the equivalent structure of the double nanoshell chain topology at an operating wavelength of 326 nm (i.e., the equivalent structure for our proposed V-type focusing device).

degrees of freedom than pure metallic structures on the tuning of resonances as well as mode coupling, we believe that the proposed nanoshell based structures could have great potential for future nanodevices.

4. CONCLUSION

In conclusion, we have proposed a new nano-focusing device based on metal-coated nanoshell chains, where focusing relies on both, the mode coupling of the SPPs and the resulting enhanced interference within scattered field. Large field intensities in the focal area are obtainable for a wide wavelength range. Equivalent structures based on correspondingly layered strips have been proposed for simplification and verification purposes. In particular, the proposed coated nanoshell configuration enables high field enhancement together with wavelength tuneability providing a reliable interface to functional planar plasmonic nanodevices.

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