Optical waves on nanoparticle chains coupled with surfaces

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Linear chains of metal nanoparticles coupled with dielectric surfaces support a variety of optical phenomena including traveling and leaky waves of several types. We investigate the chain-surface interactions and show that traveling waves can remain bound to the chain, radiate into surface wave beams, or radiate into space and surface wave beams. Radiation into surface waves may be exploited to create a leaky surface wave antenna with potential applications to surface wave microscopy. © 2009 Optical Society of America

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Many principles of Fourier optics used to manipulate waves in bulk materials can be adapted to manipulate waves propagating near dielectric or metal surfaces [1–3]. In particular, linear chains of metallic nanoparticles near a surface can support traveling waves (TWs) mediated by plasmonic resonances among the chain elements [4–10] and by the surface. Coupling between these TWs and the surface waves (SWs), though it has received little attention, can lead to new chain functionalities. The TWs on the chain can induce SWs, which may be directed into a narrow beam along the surface, thereby acting as an optical leaky SW antenna. Such leaky SWs are analogous to space leaky waves (LWs) supported by conventional LW antennas and grating couplers [11] but are bound to the surface. The surface, in turn, can affect propagation of the TWs, allowing chain elements to interact through the SWs. Understanding the properties of these waves could enable the design of novel optical devices and have applications to SW microscopy.

This Letter investigates theoretically and computationally a chain of metallic particles placed near a dielectric slab. We analyze the conditions under which the TWs propagate along the chain or radiate out of the chain. We show three types of propagating modes: modes that are bound to the chain, modes that radiate into SW beams but not into space waves, and modes that radiate into both surface and space waves. This rich variety of wave phenomena arises from interactions mediated not only by space waves but also reflected waves and SWs that are responsible for mutual coupling between the chain and the surface.

Consider a periodic chain of N gold nanoshells of permittivity $\varepsilon_m(\omega)$, assumed to follow the Drude model [12], with a silicon dioxide core of permittivity $\varepsilon_d=2.37$. The shell's inner and outer radii are r_1 and r_2, and the array has spacing d. It is assumed that $r_1, r_2, d \ll \lambda$, where λ is the operation (vacuum) wavelength (Fig. 1). The chain is located a distance h above a silicon slab of permittivity $\varepsilon_{\text{slab}}=12.5$ and thickness t_{slab}. The entire structure is embedded in a silicon dioxide medium. Although all wave phenomena are described for the particular structure in Fig. 1, the main conclusions are valid for any resonant array near metal-dielectric layered media supporting SWs.

Individual nanoshells support plasmonic resonances whose resonant wavelengths, determined by the ratio r_1/r_2 and $\varepsilon_m(\omega)$, can be much larger than their size. In a chain, the interaction among resonant nanoshells results in the existence of TW modes that are coupled with the slab. Characterizing these TW modes involves finding the chain's dispersion relations as well as characterizing the fields associated with these modes. To this end we model the nanoshells as point dipoles via their polarizabilities and assign the first shell of the array a fixed polarization to simulate a localized source excitation. We then use the dyadic Green's function for a source in a layered medium [13] to set up and solve a self-consistent matrix equation for the nanoshell's polarizations. After solving for the polarization of each nanoshell in response to the localized dipole excitation, we find the wavenumbers of TW modes propagating along the chain by identifying strong resonant peaks in the Fourier spectrum of shell polarization states. These peaks represent source-free fields supported by the chain, and their wavenumbers yield the dispersion relation. Note that unlike free-standing chains [4,5,7–9], different transverse excitation directions for the chain in Fig. 1 yield distinct TW modes. The chain radiates only into TM SWs when excited by x- and z-directed sources and only into TE SWs when excited by y-directed sources.

It is known that dense free-standing nanoparticle chains can support "slow" TWs that propagate without radiation loss, characterized by fields bound to

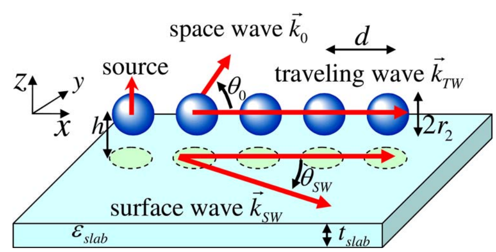

Fig. 1. (Color online) TWs on an array of nanoshells above a surface can radiate into SWs and space waves.

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the region near the chain and wavenumbers k_{TW} greater than the free-space wavenumber $k_0=2\pi/\lambda$ [6–9]. Coupling with a dielectric slab leads to new possibilities of wave guidance and radiation phenomena. For the chain TWs to be slow in this new configuration, $\mathrm{Re}\{k_{\mathrm{TW}}(\omega)\}$ must be greater than both k_0 and the SW wavenumber $k_{\mathrm{SW}}(\omega)$, i.e., $\mathrm{Re}\{k_{\mathrm{TW}}\}>k_{\mathrm{SW}}>k_0$. For smaller values of $\mathrm{Re}\{k_{\mathrm{TW}}(\omega)\}$, however, the surface interaction can lead to distinct LW behavior absent for free-standing chains. When $k_0<\mathrm{Re}\{k_{\mathrm{TW}}\}<k_{\mathrm{SW}}$ the TWs are fast (or leaky) with respect to the SWs but slow (or bound) with respect to space waves. In this case the TWs propagating along the chain will radiate ("leak") power into a narrow SW beam without radiating out of the surface plane. Such "leaky surface wave (LSW) radiation" is a fundamentally new property of the chain-surface coupled system. It also can occur that $\mathrm{Re}\{k_{\mathrm{TW}}\}<k_0<k_{\mathrm{SW}}$ and the TW radiates into both a space wave beam and an SW beam, though at different angles.

To illustrate the properties of chains coupled with a dielectric surface, we consider a chain of $N=200$ shells with parameters $r_2=30$, $r_1=21$, $d=120$, $h=120$, and $t_{\mathrm{slab}}=148$ nm. For the chosen parameters the shells have a static resonance at $\lambda_{\mathrm{res}}=600$ nm. Figure 2(a) shows the dispersion relation of the chain for the TM and the TE transverse polarizations obtained based on chain excitation by z- and y-directed sources, respectively. Note that, unlike the case of free-standing chains, the dispersion curves for the two transverse polarizations are significantly different. The two curves shown for each polarization correspond to two modes that dominate, the first with the TW wavenumber satisfying the condition $k_0<\mathrm{Re}\{k_{\mathrm{TW}}\}<k_{\mathrm{SW}}$ with $\mathrm{Re}\{k_{\mathrm{TW}}\}$ close to k_0 near λ_{res}, and the second satisfying $\mathrm{Re}\{k_{\mathrm{TW}}\}>k_{\mathrm{SW}}>k_0$ with $\mathrm{Re}\{k_{\mathrm{TW}}\}$ close to k_{SW}. Physically, this second mode is a TW that is purely bound to the region near the chain

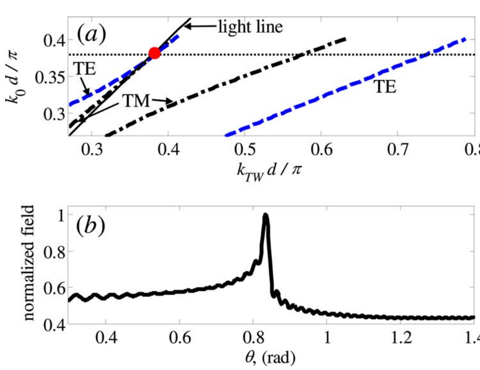

Fig. 2. (Color online) (a) Dispersion of traveling wavenumbers k_{TW} for a chain near a surface. The TE and TM curves on the left correspond to modes that radiate into TE and TM SWs, respectively, whereas the TE and TM curves on the right represent slow wave modes mediated by SW interaction and bound to the chain. The horizontal line indicates an excitation wavelength of 630 nm, and the circle marks its intersection with the TM curve, where the fields are plotted next. (b) Normalized TM SW electric field radiated by the chain along the surface, observed at a vertical displacement $z=h$ from the surface at a distance $r=k_0(Nd)^2$ and angle θ from the chain.

and is mediated by SW near-field interactions among the chain elements. The first mode, in contrast, is mediated by direct and reflected near-field interactions, and near the resonant wavelength it leaks into an SW beam but does not radiate out of the surface. At larger wavelengths the dispersion curve for this mode crosses the light line, a phenomenon resulting from direct reflected field interactions. (This transition occurs at $\lambda=662$ nm for the TM polarized mode and $\lambda=646$ nm for the TE mode.)

The angle of the SW beam with respect to the chain axis approximately satisfies the phase matching conditions

$$\theta_{\mathrm{SW}}=\cos^{-1}\{k_{\mathrm{TW}}/k_{\mathrm{SW}}\},\quad \theta_{\mathrm{SW}}>\cos^{-1}\{k_0/k_{\mathrm{SW}}\},\quad (1)$$

where θ_{SW} denotes the beam maximum in terms of the elevation angle θ with respect to the chain axis, and it is assumed that the azimuth angle defined in the $y-z$ plane is $\varphi\approx 0$ or π so that the field is observed near the surface. The second condition in Eq. (1) assumes $k_{\mathrm{TW}}>k_0$ or that no out-of-plane radiation occurs. The width of the radiated beam is determined by the chain's physical parameters and the TW loss rate, which is dominated by radiative losses. By analyzing a nonradiating chain in free space, we estimate the decay length of the array resulting from ohmic dissipation alone to be approximately 160 wavelengths at $\lambda=630$ nm, shrinking to 60 wavelengths at $\lambda_{\mathrm{res}}=600$ nm.

To confirm these predictions, we calculate, for $\lambda=630$ nm [dashed horizontal line in Fig. 2(a)], the radiated (electric) far-field strength near the slab surface for the TM polarization as a function of the angle θ (for $\varphi=0$). At this wavelength the slab supports TE and TM SWs with wavenumbers $k_{\mathrm{SW}}^{\mathrm{TM}}/k_0\approx 1.50$ and $k_{\mathrm{SW}}^{\mathrm{TE}}/k_0\approx 1.93$. Figure 2(b) shows this angular dependence at a distance of $k_0(Nd)^2$ from the chain, where the fields are dominated by the SWs and represent the SW radiated beam. It is evident that the angle of peak radiation into the far-field agrees with our prediction from the dispersion of the first TW mode via Eq. (1). This behavior has some resemblance to radiation in LW antennas, except that here the LW has a unique physical nature in that it does not radiate out of the surface. The waves are leaky only in the sense that they are not bound to the chain, even though all fields remain bound to the surface.

Additional unique wave phenomena are obtained when a double periodicity is added in the chain element distribution. These structures comprise a periodic sparse array of "defects" in an otherwise densely spaced periodic array and is conceptually similar to the structure in [14]. For example, consider the case where each N_xth element is made slightly bigger so that the resulting compound chain has a periodicity of $L_x=N_xd$. Such "weak" defects do not significantly alter the existing TW modes supported by the array, but they introduce additional radiation mechanisms. The periodicity L_x leads gives rise to source-free fields given in terms of diffraction modes corresponding to TWs with wavenumbers

$$k^{\pm}_{\mathrm{TW},n} = \pm(k_{\mathrm{TW}} + 2\pi n/L_x), \quad (2)$$

where n is an integer. Individual peaks in the TW wavenumber spectrum are repeated with the interval $\Delta\beta_x = 2\pi/L_x$, forming higher-order modes. When this spectral spacing is large enough, as with dense singly periodic chains with small $L_x = d$, all spectral peaks satisfy $|k^{\pm}_{\mathrm{TW},n}| > k_0$ so that the TW's do not radiate into space. Adding a sparse array, however, increases the chain's period L_x, decreasing the spectral spacing $\Delta\beta_x$ so that resonance peaks are closely spaced. It effectively shrinks the Brillouin zone, in other words, so that one or more of the peaks may satisfy $\mathrm{Re}\{k^{\pm}_{\mathrm{TW},n}\} < k_0 < k_{\mathrm{SW}}$. These new spectral peaks, which fall inside the light lines, correspond to leaky TW modes. They radiate into both free-space and SW beams at distinct angles with the chain axis given by

$$\theta_0 = \cos^{-1}\{k^{\pm}_{\mathrm{TW},n}/k_0\}, \quad \theta_{\mathrm{SW}} = \cos^{-1}\{k^{\pm}_{\mathrm{TW},n}/k_{\mathrm{SW}}\}, \quad (3)$$

respectively. Note that the radiation into space waves occurs along a cone with the maximum angle $\theta \approx \theta_0$ and is nearly independent of φ. From Eq. (3), it follows that the SW beam has a larger angle with respect to the chain axis, i.e., $\theta_{\mathrm{SW}} < \theta_0$.

Figure 3(a) shows the TM dispersion relations for a two-periodic chain, identical to the chain considered in Fig. 2 except the polarizability of every fourth shell is increased by a factor of 5 (equivalent to increasing r_1 and r_2 by a factor of 1.71). For this configuration higher-order diffraction modes are observed, with spacing $\Delta\beta_x = 1.32k_0$, for each mode present in the singly periodic case. The two curves on the left in Fig. 3(a) correspond to these modes, which radiate into both space waves and SWs. Figure 3(b) shows the angular dependence of the radiated fields both directly above the surface and along the surface at $\lambda = 630$ nm. The two peaks correspond to radiation from the $k^{+}_{\mathrm{TW},-1}$ TW mode into LSWs and leaky space waves. The angles at which these radiated peaks are observed are predicted correctly from the wavenumbers of the corresponding spectral peak via Eqs. (1) and (3). A chain that can radiate into space presents the possibility, via reciprocity, of coupling space waves to TWs along a chain and LSW beams along the surface.

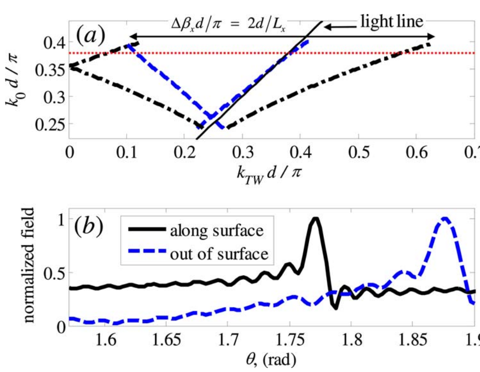

Fig. 3. (Color online) (a) Dispersion of traveling wavenumbers k_{TW} for a TM polarized two-periodic chain near a surface. The two rightmost dashed curves shown are modes that appear for the singly periodic chain, whereas the two curves on the left are higher-order modes that radiate into both SWs and free space. The horizontal line indicates an excitation wavelength of 630 nm at which the fields are plotted next. (b) Normalized fields radiated from the $k^{+}_{\mathrm{TW},-1}$ mode, a higher-order mode with negative wavenumber, observed along and above the surface, at an angle θ with the chain, and at a distance $r = k_0(Nd)^2$.

In summary, we have studied TW propagation along resonant chains of nanoshells coupled with a dielectric slab and showed that interactions between the chain and slab surface strongly affect the TW properties. Specifically, the slab surface can introduce new types of waves supported by the chain including LSWs that radiate into narrow SW beams but do not radiate out of the surface plane. Furthermore, a two-periodic chain, with two layers of periodicity, can radiate into both space waves and SWs. The identified phenomena can find uses to manipulate optical fields on metal-dielectric surfaces, which can find various applications including SW couplers and surface imaging techniques.

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References

1. I. P. Radko, S. I. Bozhevolnyi, A. B. Evlyukhin, and A. Boltasseva, Opt. Express **15**, 6576 (2007).
2. L. Feng, K. A. Tetz, B. Slutsky, V. Lomakin, and Y. Fainman, Appl. Phys. Lett. **91**, 081101 (2007).
3. Z. Liu, J. M. Steele, W. Srituravanich, Y. Pikus, S. Sun, and X. Zhang, Nano Lett. **5**, 1726 (2005).
4. M. Quinten, A. Leitner, R. Krenn, and F. R. Aussenegg, Opt. Lett. **23**, 1331 (1998).
5. W. H. Weber and G. W. Ford, Phys. Rev. B **70**, 125429 (2004).
6. M. L. Brongersma, J. W. Hartman, and H. A. Atwater, Phys. Rev. B **62**, 016356 (2000).
7. A. Alù and N. Engheta, Phys. Rev. B **74**, 205436 (2006).
8. V. A. Markel and A. K. Sarychev, Phys. Rev. B **75**, 085426 (2007).
9. R. A. Shore and A. D. Yaghjian, Electron. Lett. **41**, 578 (2005).
10. V. Lomakin, L. Meng, and E. Michielssen, Opt. Express **15**, 11827 (2007).
11. R. E. Collin and F. J. Zucker, *Antenna Theory: Part 2* (McGraw-Hill, 1969).
12. E. D. Palik, *Handbook of Optical Constants of Solids* (Academic, 1998).
13. W. C. Chew, *Waves and Fields in Inhomogeneous Media* (IEEE, 1995).
14. V. Lomakin, C. Nan-Wei, L. Shuqing, and E. Michielssen, IEEE Microw. Wirel. Compon. Lett. **14**, 355 (2004).