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Simple nanometric plasmon multiplexer

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We present a simple multiplexing structure made of two discrete plasmon wires coupled by two metal nanoclusters. We show that this simple nanosystem can transfer one plasmon wavelength from one wire to the other. Closed-form relations between the transmission coefficients and the nanocluster distances are given to optimize the desired directional plasmon ejection.

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The directional ejection of photons [1–3] from one waveguide to another one is now intensively investigated, as such transfer processes are particularly important in wavelength multiplexing and in telecommunication routing devices.

A device enabling a directional ejection of quasiparticles should let the quasiparticles of every wavelength but one travel without perturbation in the input waveguide or wire. At the same time the quasiparticle of one selected and well-defined wavelength is expected to be transferred to the other wire with a phase shift as the only admitted distortion. To meet the above requirements as closely as possible an appropriate coupling geometry should be designed.

In recent work, it has been demonstrated theoretically [4,5] and experimentally [6–9] that closely spaced metal nanoparticles arranged along a chain can interact through the near field of surface plasmon-polariton modes of adjacent particles. Such a structure for guiding the electromagnetic energy displays a mode confinement that falls below the diffraction limit of light, a property that cannot be achieved in conventional waveguides or in photonic crystals. Nevertheless, in the first experiments using spherical gold nanoparticles, the transport of electromagnetic energy along the chain cannot occur due to a large value of the attenuation coefficient (of the order of 5–6 dB per 30–40 nm). However, it was suggested theoretically [9,10] and shown in a recent experiment [11] that the attenuation coefficient can be significantly reduced by using spheroidal silver nanoparticles. In this case, the guiding of the electromagnetic wave along the chain becomes possible and an attenuation coefficient of 6 dB per 200 nm has been estimated.

In the present paper we describe a simple system, which under certain conditions realizes the directional transfer of a plasmon with a good selectivity. The system is depicted in Fig. 1. It consists of two wires made out of a periodic sequence of equidistant metallic clusters. The distance between the neighboring clusters within each wire is d. These input and output wires go, respectively, through clusters (1, 2) and (3, 4). Two additional clusters 5 and 6 of the same metal and of the same size as the wire ones are deposited between the two wires. The cluster 5 lies at an equal distance d_1 from the clusters 1 and 4. The same distance separates the clusters 6 and, respectively, clusters 2 and 3. The distance between clusters 5 and 6 is called d_2. The second nearest neighbor distances between clusters 5 and (2 or 3), and 6 and (1 or 4) are called d_3. Because of the geometry of the device, one has

$$d_3^2 = d_1^2 + d d_2 . \tag{1}$$

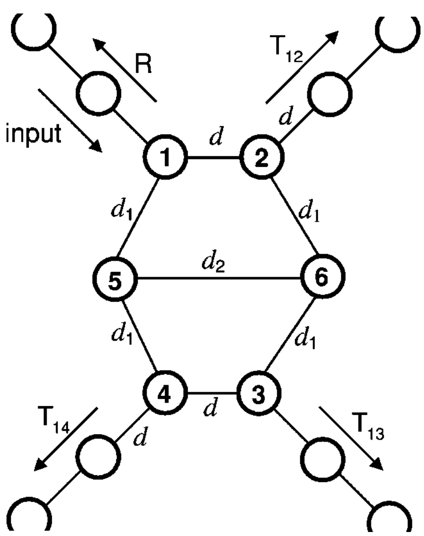

FIG. 1. One possible multiplexer geometry made out of identical clusters of radius r. The cluster nearest neighbor distances within the wires are d. The two clusters 5 and 6 are d_2 apart and they lie at the distance d_1 from the clusters (1, 4) and (2, 3), respectively.

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Being so defined the system shows two perpendicular mirror symmetry planes.

When the nanometric cluster sizes are smaller than the wavelength λ of the exciting light an oscillating dipole field is produced by the plasmon excitations. One must analyze any given cluster structure through use of the full Maxwell equations, since, of course, retardation plays an essential role in its response. The usual approach is to extend the well-known Korringa-Kohn-Rostecker (KKR) method to the description of the multiple scattering of vector electromagnetic waves from these structures. The theory, while straightforward in principle, requires rather extensive computer calculations.

However, for nanoscale structures such as those of interest in the present paper, the particle sizes and separations are small enough so that retardation effects play only a minor role. One can thus discuss the electromagnetic collective modes of such systems along with their response to probing fields within a quasistatic approach, with retardation neglected [5,12].

In the quasistatic limit considered here the coupling strength ω_1^2 between two clusters is inversely proportional to the third power of the cluster separation as long as the separation is kept small compared to the wavelength λ. Each cluster is characterized by its resonance angular frequency ω_0, which corresponds to a wavelength λ_0. We retain here the first and second nearest neighbor interactions and include damping effects. The plasmon-polariton dispersion relation of the transverse modes polarized perpendicularly to the substrate surface in an infinite and isolated chain array of the nanoclusters reads [5]

$$\omega^2(k)=\omega_0^2+2\omega_1^2\cos(kd), \tag{2}$$

where $k=2\pi/\lambda$ is the Bloch wave vector of the chain plasmon wave.

Generally, as a result of scattering processes, a reflected wave will appear at the node 1 along with three transmitted waves at nodes 2, 3, and 4, respectively.

The corresponding reflection and transmission coefficients are functions of the wavelength λ. They are conveniently expressed by the following formulas (see Ref. [3] for similar considerations):

$$R=T_{11}=|z_1+z_2+z_3+z_4-1|^2, \tag{3a}$$

$$T_{12}=|z_1+z_2-z_3-z_4|^2, \tag{3b}$$

$$T_{13}=|z_1-z_2+z_3-z_4|^2, \tag{3c}$$

$$T_{14}=|z_1-z_2-z_3+z_4|^2, \tag{3d}$$

where

$$z_n=\frac{i}{2(i+y_n)}, \quad n=1,2,3,4, \tag{4}$$

and

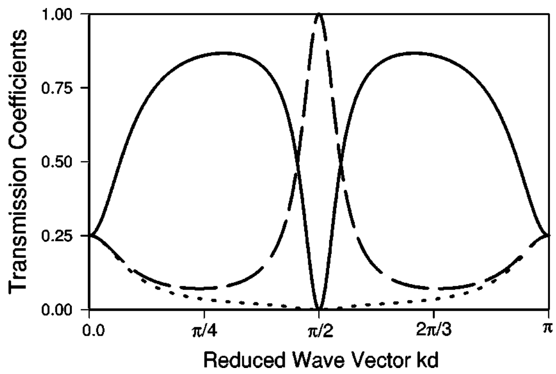

FIG. 2. Transmission coefficients T_{13} (solid line), T_{12} (long dashed line), and T_{14} (dotted line) as a function of the reduced wave vector *kd* for the system of Fig. 1 with the parameters $d=16$ nm, $d_2=24$ nm, and $d_1=19.6$ nm.

$$y_1=y_2-\frac{2[(d/d_1)^3+(d/d_3)^3]^2}{\sin(kd)[(d/d_2)^3-2\cos(kd)]}, \tag{5a}$$

$$y_2=\tan\left(\frac{kd}{2}\right), \tag{5b}$$

$$y_3=-\left[\tan\left(\frac{kd}{2}\right)\right]^{-1}, \tag{5c}$$

$$y_4=y_3+\frac{2[(d/d_1)^3-(d/d_3)^3]^2}{\sin(kd)[(d/d_2)^3+2\cos(kd)]}. \tag{5d}$$

One notes that the reflection into the wire 1 and the transmission into the wire 4 are always equal for every wavelength in this kind of plasmon-polariton systems independently of all the parameters,

$$R=T_{14}. \tag{6}$$

When attenuation is neglected, the total plasmon transfer from the input 1 to the output 3, i.e. $R=0$, $T_{12}=0$, $T_{13}=1$ and $T_{14}=0$ can be realized near the angular eigenfrequency of the isolated cluster. The corresponding wavelength $\lambda_0=2\pi/k_0$ and the distances d, d_1 and d_2 then should fulfil the following conditions:

$$\cos k_0d=-\frac{d^6}{(d_1d_3)^3} \tag{7}$$

and

$$\left(\frac{d}{d_2}\right)^3=\left(\frac{d}{d_1}\right)^6+\left(\frac{d}{d_3}\right)^6. \tag{8}$$

When attenuation is neglected, the phase factor between the wave directionally transferred to the node 3 with respect to the incident wave at the node 1 is

$$e^{i\varphi}=e^{ik_0d}. \tag{9}$$

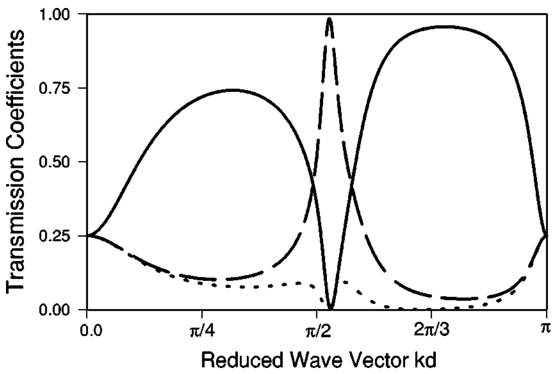

FIG. 3. Same as Fig. 2, but with inclusion of the second nearest neighbor effects and the parameter $d_3 = 27.7$ nm.

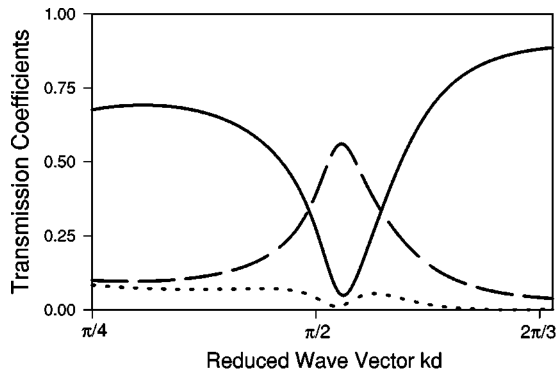

FIG. 4. Same as Fig. 3, but an energy attenuation length of the order of 6 dB per 200 nm was taken into account.

To give an illustrative and at the same time realistic example complying with the above assumptions we consider metallic clusters with a diameter of 6 nm. Those in the wires were taken to be $d = 16$ nm apart. Then, according to the above conditions one has $d_1 = 19.6$ nm, $d_2 = 24$ nm, and $d_3 = 27.7$ nm.

Figure 2 presents the transmission coefficients T_{13}, T_{12}, and T_{14} $(=R)$ as a function of the reduced wave vector *kd* in the whole range of the transmission band of the wires when the second nearest neighbor interactions and damping effects are neglected. These results are given by the above equations in the limit when $d_3 \rightarrow \infty$. One remarks the reflection symmetry with respect to $kd = \pi/2$ as well as the common value 1/4 of all the transmission coefficients at the band border. The peak in the transmission coefficient T_{13} shows a width at the half maximum equal to $\Delta(kd) = 0.29$ which corresponds to the width in the wavelength scale $\Delta(\lambda) = 0.738d = 11.8$ nm.

The symmetry of the system and the fact that all the nanoclusters involved in the example studied here are identical underlies the symmetry of the curves in Fig. 2. A shift of the directional ejection peak would occur if the nanoclusters 5 and 6 were different from those in the wires, since as a rule, the directional ejection takes place at the eigenfrequency of the coupling clusters. This indicates how the directional ejection wavelength may be controlled by selecting the appropriate parameters of the system.

In Fig. 3 we present the same results as in Fig. 2 but with inclusion of the second nearest neighbor effects. Note the shift in the position of the resonance peak and its small asymmetry.

Figure 4 now gives the modification introduced when an energy attenuation length of the order of 6 dB per 200 nm was taken into account. Such an attenuation was observed in a recent experiment for such a straight guide for clusters with a diameter of 30 nm [11].

One sees that the multiplexing effect reported here should be observable. One may expect further progress for such systems, in particular less attenuation. In that case, the results presented here will be improved.

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