Selective switch made from a graded nanosandwich chain

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The magnetic plasmon (MP) modes in a metallic nanosandwich chain with a linearly increasing spacing along the chain has been investigated. Because of the graded coupling between nanosandwiches, the MP gradon with special field localization and large field amplitude can be found in the chain as well as the extended mode, which differs from the case of periodic chain. Using this property, we can precisely control the field in the chain and guide it to different ports at different frequencies, which works as a selective switch and may have potential application in integrated optics. Finally, we give out the underlying physical mechanism to help better understand and apply this graded chain. © *2008 American Institute of Physics*. [DOI: 10.1063/1.3023064]

The subwavelength waveguides made of chains of noble metal nanoparticles have attracted wide attention recently.[1–6] Because these waveguides can support coupled surface plasmon modes that confine the electromagnetic field to the chains themselves, one can get a small waveguide with the size even able to overcome the diffractive limit. On the other hand, the waveguide based on coupling of magnetic resonance in a chain of connected single split ring resonator (SSRR) has been reported, too.[7] The merits of energy transportation through magnetic plasmon (MP) modes have also been presented, such as low radiation loss and long propagation length compared with the coupled electric resonance in a nanoparticle chain. However, the saturation of the magnetic response of the split ring resonator prevents it from having a higher frequency.[8] Moreover, the complicated shape and narrow gap of the SSRRs add to the difficulty of experimentally investigating it. In this context, scientists introduce the metallic trilayer structure (nanosandwich) for its simple structure and high working frequency.[9,10] In our previous work, we investigated a MP waveguide made of a periodic chain of nanosandwiches, which aims at getting the same merits of SSRR chain when working at a higher frequency region.[11] Besides working as a waveguide, the nanosandwich chain can present more special properties when the structure of the chain changes. In this article, we design a nanosandwich chain with the spacing between nanosandwiches increasing linearly along the chain. The MP modes supported in this chain are investigated, and both the MP gradon and extended modes are observed. By using these modes, we can precisely control the field in the waveguide to choose different ports at different frequencies, which makes this MP waveguide as a selective switch.

In Fig. 1(a), a nanosandwich that has been considered is presented. It is well known that this nanosandwich structure can produce a magnetic resonance in the middle dielectric layer by the counterdirectional currents induced in the two metal slabs.[9,10] Here, we choose glass with refractive index $n=1.5$ as the dielectric layer and the outside surrounding, and we choose gold as the metal with Drude-type dispersion, $\omega_p=1.37\times 10^{16}$ rad/s, and $\gamma=12.24\times 10^{13}$ rad/s.[12] We use a finite-integration technique (CST MICROWAVE STUDIO) to get the spatial field of the system at different frequencies. For $a=b=200$ nm and $h=50$ nm, the nanosandwich can produce a magnetic resonance at about 250 THz. The magnetic field distribution at the magnetic resonant frequency is also shown in Fig. 1(a).

Then we will focus on the chain composed of such nanosandwiches with the spacing between nanosandwiches linearly increasing along the chain, which indicates a graded change of coupling between nanosandwiches. Here, we consider a chain with 41 nanosandwiches, and the spacing d_m obeys the following rule:

$$d_m = 225 + 100[(m-1)/39], \qquad (1)$$

where m denotes the spacing between the mth and $(m+1)$th nanosandwiches. After getting the spatial magnetic field distribution of the chain, we employ a Fourier transformation method to obtain the effective dispersion relation of the excited MP modes of such coupled resonator system,[11,13]

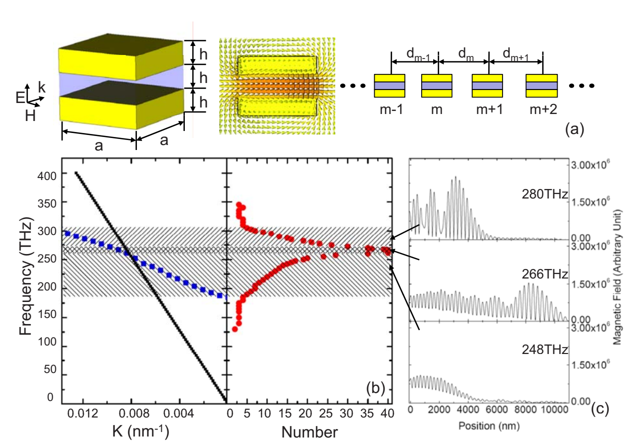

FIG. 1. (Color online) The geometry of a metallic trilayer structure, the magnetic field distribution at the magnetic resonant frequency, and the model of the graded nanosandwich chain are shown in (a). The effective dispersion relation and the propagation length of the chain are shown in (b), and the magnetic field localizations at three different frequencies are presented in (c).

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$$H(\omega,k) = \int H(\omega,x)e^{ikx}dx. \quad (2)$$

It should be mentioned that one cannot define the wavevector in a rigorous sense in the graded system in the absence of translational invariance. Here, we choose the wavevectors corresponding to the peaks of $H(\omega,k)$ at different frequencies to form the effective dispersion relation, which is plotted in Fig. 1(b), as well as the propagation length, which is translated into the numbers of the nanosandwiches in the chain. A band of MP modes is excited ranging from 188 to 300 THz, crossing with the light line at about 260 THz. Naturally, the MP modes above the light line have short propagation lengths for their leaky properties. However, different from the case of a periodic nanosandwich chain, those MP modes below the light line are no longer all extended modes. In this chain, since we actively modify the positions of the nanosandwiches, we get the graded coupling between the nanosandwiches along the chain and a special localization type of field can be obtained. Three different types of magnetic field localization at three different frequencies are plotted in Fig. 1(c). Above the light line at 248 THz, the MP mode is an evanescent mode, with the field amplitude decreasing exponentially. At 266 THz, the MP mode is an extended mode; the field can propagate throughout the chain. At 280 THz, although the MP mode is below the light line, the field in the chain cannot reach the end of the chain but stops at the middle of the waveguide, which is a typical field localization in the graded structure. Since this mode is at the high frequency region of the MP mode band, it is called "light gradon."[14] In the quasistatic case, one can even get a "heavy gradon" with the frequency below the extended mode region.[14] However, in an incremental spacing grading system, this kind of localization has not been observed, which is consistent with the theoretical work on the graded plasmonic chain.[15] It may be considered that the evanescent modes and the light gradon modes have similar properties in locating the field at the special part of the chain. However, after comparing the field distributions of these two types, we can find that the field amplitude of light gradon is much larger than that of the evanescent mode. Moreover, near the end part of the light gradon, the field is enhanced to about two times of that at the beginning of the chain, which may be useful for field transportation at this position. On the other hand, as for the evanescent mode, the field amplitude is lower and reduces almost monotonously, which makes the transport of energy difficult.

By using this property, the nanosandwich chain can work as a selective switch to guide the field to different ports at different frequencies. In Fig. 2, a series of selective switches made from this chain are plotted. The models of two two-port switches are shown in (a) and (e) with different working frequencies. For the switch [Fig. 2(a)], the graded nanosandwich chain plays the role of producing different field localizations, such as gradon and extended mode, and a periodic nanosandwich chain placed about 2.5 μm away from the first nanosandwich (nearby the 11th nanosandwich) works as a waveguide of Port 1. It is shown in Fig. 1(b) that in the chain, the field with the frequency below 288 THz can reach the 11th nanosandwich and at about 269.6 THz the field can reach the end (Port 2). By choosing well the shape of the nanosandwiches and unit cell of the waveguide of Port 1, we can get rid of the leakage at Port 1 when the magnetic field reaches Port 2. Here, the nanosandwich is chosen to be $a=200$ nm and $b=190$ nm, and the unit cell is 270 nm. The magnetic field distributions in the switch at 296, 283, and 264 THz are shown in (b)–(d), which correspond to the "OFF" mode, "Port 1 ON" mode, and "Port 2 ON" mode, respectively. Because the frequency matches with the MP mode of the waveguide of Port 1, it can guide the energy totally from the graded chain to Port 1, leading to the transportation efficiency of above 95%. Moreover, the transportation efficiency at Port 2 is more than 50%. For the second two-port switch [Fig. 2(e)], the waveguide of Port 1 is placed about 4.3 μm away from the first nanosandwich (nearby the 18th nanosandwich), with the working frequency for Port 1 ON mode being different from the first one. We choose the shape of nanosandwiches to be $a=b=200$ nm and unit cell of the periodic waveguide to be 250 nm. The magnetic field distributions at 287, 277, and 264 THz are plotted in (f)–(h), corresponding to the OFF mode, Port 1 ON mode, and Port 2 ON mode, respectively. We get the transportation efficiencies of 77% and 50% from Port 1 and Port 2.

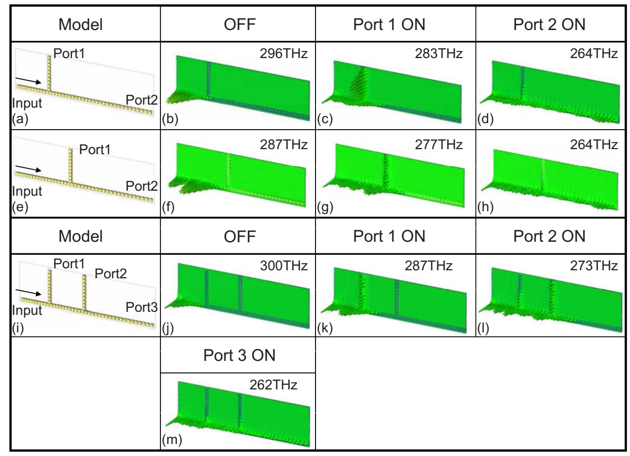

FIG. 2. (Color online) The model of the selective switches and the magnetic field localization in the switch at different frequencies.

Then, we try to add one more port to the switch to make a three-port switch. The geometry parameters are as follows. The waveguide of Port 1 is placed 2.24 μm away from the first nanosandwich (nearby the 10th nanosandwich), with $a=200$ nm, $b=180$ nm, and the unit cell of 260 nm, and the waveguide of Port 2 is placed 5.1 μm away from the first nanosandwich (nearby the 21st nanosandwich), with $a=200$ nm, $b=195$ nm, and the unit cell of 275 nm. The model of the three-port switch is shown in (i). We can get the transportation efficiencies of Port 1, Port 2, and Port 3 to be 65%, 55%, and 40%, respectively. The magnetic field distributions at four frequencies are shown in (j)–(m), corresponding to OFF mode, Port 1 ON mode, Port 2 ON mode, and Port 3 ON mode, in which we can see that the graded nanosandwich chain can work well as a three-port switch. We can see that at the Port 2 ON mode, the field propagates in the waveguide to Port 1. However, due to the special design of the waveguide, the frequency of field does not match the MP mode of the waveguide. Therefore, it just propagates a short distance and vanishes. It should be noticed that the transportation efficiencies of the ports are de-

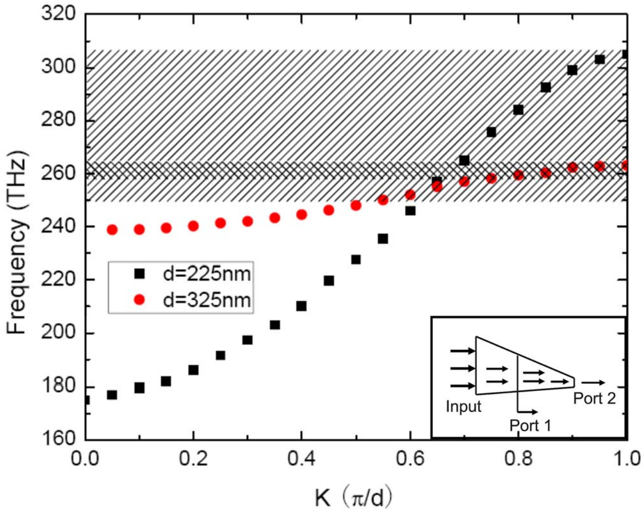

FIG. 3. (Color online) Plot of the dispersion relation of the periodic nanosandwich chains with $d=225$ nm and $d=325$ nm. The shadow regions correspond to the MP modes below the light line. The sketch map of the physical mechanism of the graded nanosandwich chain is shown in the inset.

pendent on both the MP gradon modes of the graded nanosandwich chain and the structure waveguide of the ports. Moreover, it is possible to further improve the transportation efficiencies by modifying the structures of both the graded nanosandwich chain and the waveguide of the ports.

Finally, we would like to discuss the underlying physical mechanism of this system to help better understand and apply the graded chain. Assuming every pair of nanosandwiches as a periodic chain, the linearly increasing spacing can get a special MP mode band corresponding to different pairs at different positions of the chain. The first pair of nanosandwiches ($d=225$ nm) can be considered as a gate to determine the frequency region of the MP mode band, the dispersion relation of which is plotted in Fig. 3. With increasing spacing along the chain, the coupling between nanosandwiches decreases and the bandwidth of the extended MP modes also shrinks. Near the end of the chain, only the extended MP modes of the periodic chain with the spacing of $d=325$ nm (corresponding to the last pair) can pass through the chain. The graded chain works as a filter to gradually get rid of the field with the frequency within the band region of $d=225$ nm and outside the band region of $d=325$ nm along the chain. So if we place a waveguide near the nanosandwich at the middle of the chain, we can pick up the field that will be filtered, thus leading to a selective switch dependent on frequency. A sketch map of this physical mechanism is shown in the inset. By tuning well the spacings of the first and last nanosandwich pairs, we can tail the selective switches with special working frequencies according to our requirement.

In summary, we investigated the MP modes in the nanosandwich chain with a linearly increasing spacing between the nanosandwiches. Because of the special structure, the chain can sustain different field localization types, such as light gradon and extended mode. By using these modes, we can make a selective switch to guide the field to different ports at different frequencies, which has a potential application in the integrated optics. Finally, the physical mechanism of the system is also discussed to give out a clear physical picture.

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