Magnetic plasmon modes in periodic chains of nanosandwiches

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Abstract: The magnetic plasmon (MP) modes in periodic chains of metallic trilayer nanostructures (nanosandwich) have been investigated numerically in optical frequency region. By employing the Fourier Transformation (FT) method, the MP modes excited in these chains can be observed directly. We have also used different exciting sources to excite the MP modes in the chain so that we can get clearer physics picture and richer information of the nanosandwich chain. For their long propagating lengths, the nanosandwich chains can well work as subwavelength waveguides to transport electromagnetic field. And one can easily tune the working frequencies and band width of the MP modes by changing the parameters of these chains.

OCIS codes: (240.6680) Surface Plasmons; (260.2030) Dispersion; (260.5740) Resonance.

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1. Introduction

Recently, sub-wavelength waveguides made of chains of noble metal nanoparticles have attracted considerable attention [1, 2, 3, 4, 5, 6]. Because of the strong coupling of surface plasmon resonances of the nanoparticles, electromagnetic field is highly confined around the chains. Therefore, these waveguide can even overcome the diffractive limit, which may have potential application in Integrated Optics. On the other hand, the sub-wavelength waveguide based on the magnetic plasmon (MP) excited in a chain of connected SSRRs (single split ring resonator) has also been reported [7]. The merits of energy transport through MP have been presented, such as the low radiation loss and the long propagating length. However, the saturation of the magnetic response of the SRR (split ring resonator) at high frequency prevent this structure from higher frequency [8]. And the complicated shape and narrow gap of the SSRRs keep us from experimentally investigating it.

To this end, scientists introduce many new structures to realize magnetic resonance in high frequency regime, such as fish-net [9, 10, 11], nanorod pairs [12], and nanosandwich [14, 15]. It is shown that the negative permeability and even negative refractive index can be obtained from the fish-net and nanosandwich structures [9, 14, 15]. The magnetic plasmon polariton (MPP) mode in the fish-net structures and the coupling of MPs in a three-metal-layer structure have also been reported recently [10, 11]. Additionally, using the magnetic resonance between two closely put nanorods, one can transport energy through a waveguide made of two coupled nanorod chains in high frequency regime [12].

As one of the basic building block in Plasmonics, it is a good choice to use the nanosandwich structure to make a subwavelength waveguide in high frequency regime for its simple structure and high working frequency regime. Fig. 1(a) presents the geometry of single nanosandwich. Two metallic slabs are separated by a dielectric layer, with the metal being gold owning Drude-type dispersion, $\omega_p = 1.37 \times 10^{16}$rad/s and $\gamma = 12.24 \times 10^{13}$rad/s [10]. The dielectric layer and the outside environment is assumed to be glass with refractive index being 1.5. When placing an external magnetic field parallel to the dielectric layer, a large magnetic field can be excited in the middle layer. The excited magnetic field is recorded by a probe inserted into the middle of the dielectric layer, which is plotted in Fig. 1(b) as a function of frequency. At about 2.5×10^{14}Hz, the magnetic field reach the peak, indicating a magnetic resonance. The magnetic field in z=0

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plane is plotted in Fig. 1(c), in which a magnetic resonance is excited with the direction along y-axis. The electric field at y=0 plane is shown in Fig. 1(d). It is the anti-symmetric pair of electric dipoles that forms the magnetic resonance in the nanosandwich. The similar results have been reported by previous works [14, 13]. In fact, there exist higher magnetic modes in the nanosandwich at higher frequencies. For simplicity, we just investigate the coupling of the first magnetic resonant modes in the periodic chains of nanosandwiches in this work.

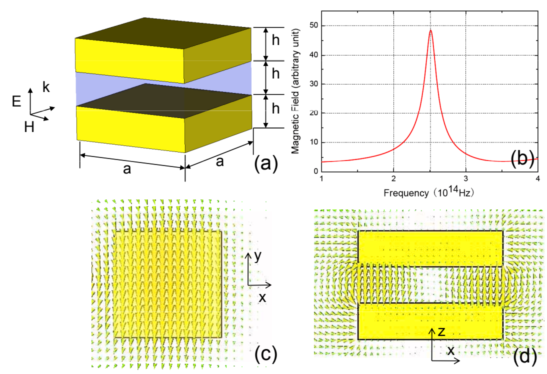

Fig. 1. The geometry of a nanosandwich is shown in (a), with $h = 50nm$ and $a = 200nm$. The magnetic field at the middle layer of the nanosandwich is presented in (b) at the function of frequency. The magnetic field at z=0 and electric field at y=0 are plotted in (c) and (d).

2. Fourier transformation (FT) method

Before going to the results, we would like to mention something about the processing method used in this work. We use the finite-difference time-domain method (CST MICROWAVE STUDIO) to obtain the magnetic field distributions at different frequencies. An FT method is employed to do the transformation from spacial region to wave vector region, so that we can easily observe the value of magnetic field of every state in the $\omega - k$ space, and get the information of the MP modes excited in the chain according to their values [16].

$$H(\omega,k) = \int H(\omega,x)e^{ikx}dx \tag{1}$$

The conventional method to solve this coupled resonators problem is to use the dipole approximation considering each resonator to be a dipole [1, 2, 3, 4, 5]. However, it is difficult to get an secular solution from the self-consistent coupled dipole equations in a realistic case, in which the radiation and retardation are included. Moreover, in this case, the magnetic field excited in the nanosandwich distributes in a wide area in the dielectric layer, which is better to be considered as an area rather than a point, especially for a close interparticle spacing. And the electric coupling between the nanosandwiches is complicated. By using the FT method, we needn't consider the approximation and the coupling mechanism any more. We can directly get the excited MP modes from the FT results. Because the excited magnetic field in the nanosandwich concentrates in the middle layer and reach the peak at the middle plane, we just need to process the field along the chain at the middle plane. And since we pick up the magnetic field from the realistic model, using different exciting sources will lead to different MP modes excited in the chain.

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3. Results and discussions

3.1. MP modes with different exciting sources

We assume that the nanosandwich chain is embedded in glass, with the periodicity of to be 250*nm* and the number of the periods to be 20. We firstly place a current line source (a current with length of 150nm and current I=1A) 200nm in front of the chain with the direction of current normal to the chain, so that the radiated magnetic field can excite the magnetic resonance in the nanosandwiches of the chain. The magnetic field in the middle plane z=0 and the electric field in y=0 plane are plotted in Fig. 2(a) and 2(b) at 2.7×10^{14}Hz. It is shown that the magnetic resonances excited in the nanosandwiches with the direction perpendicular to the chain, which forms the magnetic plasmon in the chain. To show the sub-wavelength property, we also investigate the power flow in the chain and find the power flow is only confined in the middle dielectric layers in the nanosandwiches of the chain. The power flow at the last nanosandwich is plotted in Fig. 2(c). The field is confined in the space ranging from y=-125nm to y=125nm, which is smaller than the wavelength in glass (740nm).

The $\omega-k$ map calculated by FT method is shown in Fig. 2(e) with a sketch of the system plotted in Fig. 2(d). Different colors in the map correspond to different values of $H(\omega,k)$ calculated from Eq. 1 at the modes in the $\omega-k$ space. The large value of$H(\omega,k)$ corresponds to the excited MP mode of the modes. It is evident that a band of modes ranging from 2.8×10^{14}Hz to 2.1×10^{14}Hz are excited in the chain. We can conclude that these modes are caused by exciting of MP in the chain, since they just extend around the magnetic resonant frequency of single nanosandwich, which is quite similar with the energy band structure of 1D periodic atom chain in the solid state physics. The MP modes cross with the light line (the black dot line) at about 2.6×10^{14}Hz, and they are divided into two parts by the light line. Above the light line, the MP modes are much weaker than those below the light line for their leaky property. And we also observed that the free propagating modes (corresponding to the light line) exist together with the MP mode above the light line.

As we have just mentioned, with different exciting sources, the way of the MP modes excited in the chain will change. We put a current line above the first nanosandwich with the current parallel to the chain, of which the sketch is shown in Fig. 2(f). Since the current line radiate weakly along the direction of the current, it can be considered that there is no magnetic field propagating along the chain and only the first nanosandwich is excited, while the magnetic field in other nanosandwiches are excited by the front ones. Because the electric field and magnetic field have the similar distribution pattern as the first case, we won't show them here. After using the FT method, a clearer dispersion relation of the MP modes is presented in Fig. 2(g) in comparison with Fig. 2(e). Especially near the cross point with the light line, the MP modes anticross with the light line and are cut into two separate parts, which is quite similar with the results of eigenmodes of nanoparticle chains [4]. Moreover, the strongest part of the MP modes is at the middle of MP modes below the light line, while in Fig. 2(e), the strongest part is closer to the cross point. Investigating the modes excited by the third exciting source will enable us to understand this phenomenon.

This time, we use a plane wave source to excite the MP modes in the chain. The sketch of the system is shown in Fig. 2(h) and the FT results are shown in Fig. 2(i). It is shown that only the MP modes below the light line still remain, while they are much weaker than the free propagating modes (corresponding to the light line). Those above the light line vanish. At the cross point between the light line and the MP modes, $H(\omega,k)$ reach the peak. It can be understood that the MPP is excited at this point, which resulting from the coupling between the plane wave and nanosandwich chain [10]. As a result, when we compare it to the first and second cases in Fig. 2(e) and Fig. 2(g), we can conclude that the first case is the compound result of both the second and third case, because the magnetic field radiated by the current

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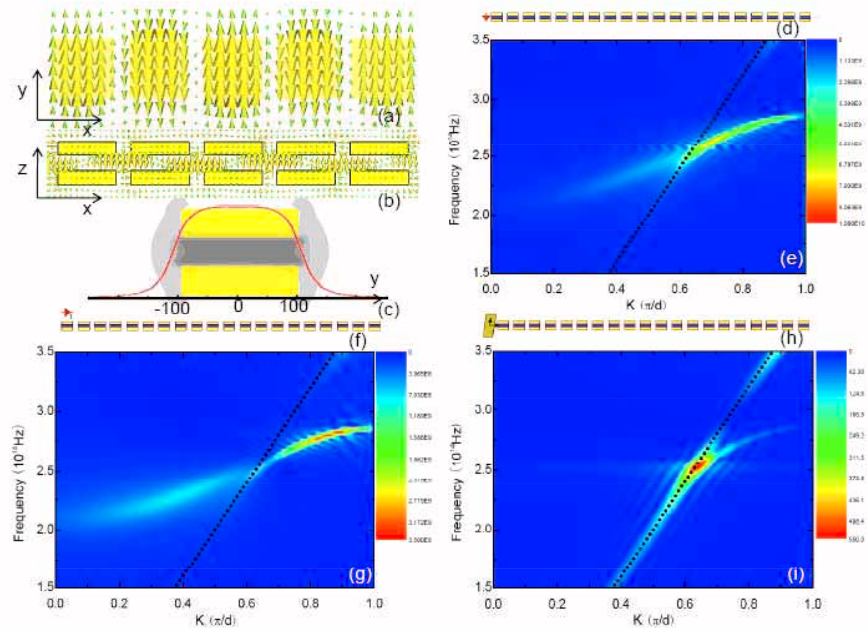

Fig. 2. The magnetic field in z=0 plane, electric field in y=0 plane and the power flow in x=10μm are presented in (a)-(c), respectively. The red line in (c) corresponds to the power flow at z=0. The FT maps for three different sources are shown in (e), (g) and (i), with the sketches of the systems plotted in (d), (f) and (h).

line in the first case can not only excite the magnetic resonance in the first nanosandwich (like the second case), but also propagate along the chain to excite the other nanosandwiches (like the third case). Therefore, by using the different exciting sources, we can get a clearer physics picture and rich information about the MP modes sustained in the nanosandwich chain, and the FT method is quite efficient in treating this structure.

3.2. Band engineering

We also investigate the decay coefficient $\alpha = 1/Im[k]$ in the chain with the number of period to be 200, which is shown in Fig.3(a). The shadow part corresponds to the MP modes. Two different patterns remark the two parts of modes above and below the light line, respectively. It is evident that the modes below the light line own smaller decay coefficients (longer propagating length) than those above the light line. The propagating length of the modes below the light line can be more than $10\mu m$, whichenables the chain to play as a waveguide in the Integrate Optics. The working frequencies (the modes below the light line) of the waveguide can be as wide as about 5×10^{13}Hz, ranging from 2.5×10^{14}Hz to 3×10^{14}Hz. By changing the interparticle spacing between the nanosandwiches of the chain, one can easily change the coupling between the nanosandwiches, in order to tune the working frequency and the band width of the MP modes. Fig.3(b) and Fig.3(c) present the excited MP modes and decay coefficients with interparticle spacing to be $d = 225nm$ and $d = 300nm$, respectively. With a closer spacing, the coupling between nanosandwiches increases, leading to an extended band. Therefore, with $d = 225nm$, the band width is extended to twice the width, from 1.75×10^{14}Hz to 3.1×10^{14}Hz. And the propagating length also increases to more than $30\mu m$ in the part below the light line.

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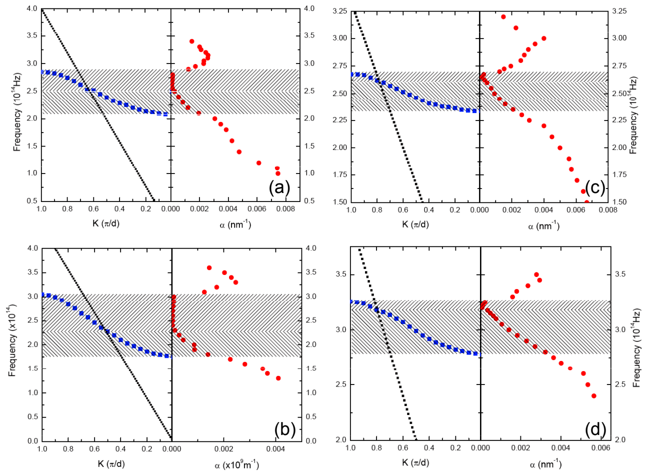

Fig. 3. The dispersion relation of k and α with (a) $a = 200nm$, $d = 250nm$; (b) $a = 200nm$, $d = 225nm$; (c) $a = 200nm$, $d = 300nm$; (d) $a = 150nm$, $d = 250nm$.

On the contrary, with a wider interparticle spacing, the coupling between the nanosandwiches reduces and the band of MP modes will shrink. With $d = 300nm$, the band width reduces to less than 0.15×10^{14}Hz from 2.72×10^{14}Hz to 2.6×10^{14}Hz, which can be considered as a frequency filter, with the propagating length being more than $5\mu m$ below the light line. Besides changing the coupling to tune the MP mode band, one can also directly change the geometry of the nanosandwiches to engineer the MP resonance frequency. Fig.3(d) shows the dispersion relation of the excited MP modes in the chain with $a = 150nm$ and $d = 250nm$. The MP modes are tuned to higher frequencies from 2.8×10^{14}Hz to 3.25×10^{14}Hz as well as the MP resonance frequency of single nanosandwich, which is not shown here. The working frequencies ranges from about 3.15×10^{14}Hz to 3.25×10^{14}Hz, with propagating length being more than $20\mu m$.

4. Conclusion

We investigate the MP modes excited in periodic chains composed of nanosandwiches. The FT method is used to directly observe the MP modes in these chains. We get different results of excited MP modes by using different exciting sources, so that we can get a clear physics picture and more information of the system. We also find the nanosandwich chains have long propagating length, which enable them to work as subwavelength waveguides in the Integrated Optics. And the working frequencies and the band width of the excited MP modes can be easily tuned by changing the coupling between the nanosandwiches and directly modifying the magnetic resonance frequency of single nanosandwich.

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