Magnetic plasmon mode resonance and power transmission in a nanosandwich waveguide*

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The magnetic plasmon (MP) modes in the metal–dielectric–metal nanosandwich structure are investigated numerically, and the principle of energy resonance in such a resonator is proposed. An equivalent inductance capacitance circuit analysis method is proposed and the results are in agreement with the numerical simulations. Based on the MP resonance in such a structure, a nanosandwich chain waveguide is designed. Gold and silver are chosen as the metal materials. The power transmission efficiency of the nanosandwich waveguide can be as high as 0.546 in a specific nanosandwich unit cell, even when the metal absorption loss is large, which is the perspective of the new waveguides and lasers based on MP modes.

Keywords: nanosandwich, magnetic plasmon modes, magnetic resonance, waveguide

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1. Introduction

Due to the low radiation loss and the long propagation length of plasmon[1,2] modes in the form of magnetic plasmon resonance,[3,4] many structures are introduced, such as split ring resonators,[5,6] fishnet,[7] nanorod pairs,[8] and slit-hole resonators.[9] One major problem for these structures is the saturation of the magnetic response at high frequency.[10] Nanosandwich structures[11,12] can overcome such a problem and can be experimentally investigated for their simple structure, so nanosandwich structures have attracted considerable attention.[13−15] Another advantage of nanosandwich structures is that the electromagnetic field is strongly confined, which can overcome the diffractive limit and may have potential applications in integrated optics. However, most of the studies of nanosandwich structures have not povided an equivalent inductance capacitance circuit analysis method to illuminate the MP mode resonance and the waveguide transmission in such structures.

In this paper, the excitation and the field distribution of the MP modes are investigated in a nanosandwich structure. We study the change tendency of the resonance frequency and explain it theoretically. The MP mode resonance frequency and the power transmission in the nanosandwich waveguide are also analysed. Furthermore, we compare the power transmission efficiencies with using silver and gold as the metal slab separately and investigate the enhancement of the energy transmission aroused by the magnetic resonance in the waveguide unit, which will give guidance in the design[16,17] of the device based on MP modes.

2. Model and calculation

Figure 1(a) shows the geometry of the nanosandwich structure. Two metallic slabs are separated by a dielectric layer. The metallic slabs are of gold, following the Drude-type dispersion, $\omega_{\rm p} = 1.37 \times 10^{16}$ rad/s and $\omega_\tau = 40.69 \times 10^{12}$ rad/s.[18] The dielectric layer and the background are assumed to be of glass with a refractive index of 1.5. When an external magnetic field is applied in the direction parallel to the middle layer, as shown in Fig. 1(b), a large magnetic field can be induced in the middle layer. The magnetic resonance as a function of wavelength (resonance peck $\lambda = 1212$ nm) is shown in Fig. 1(c) with the following parameters: thickness of metal layer $a = 50$ nm, thickness of dielectric layer $b = 50$ nm, and length of square $c = 200$ nm.

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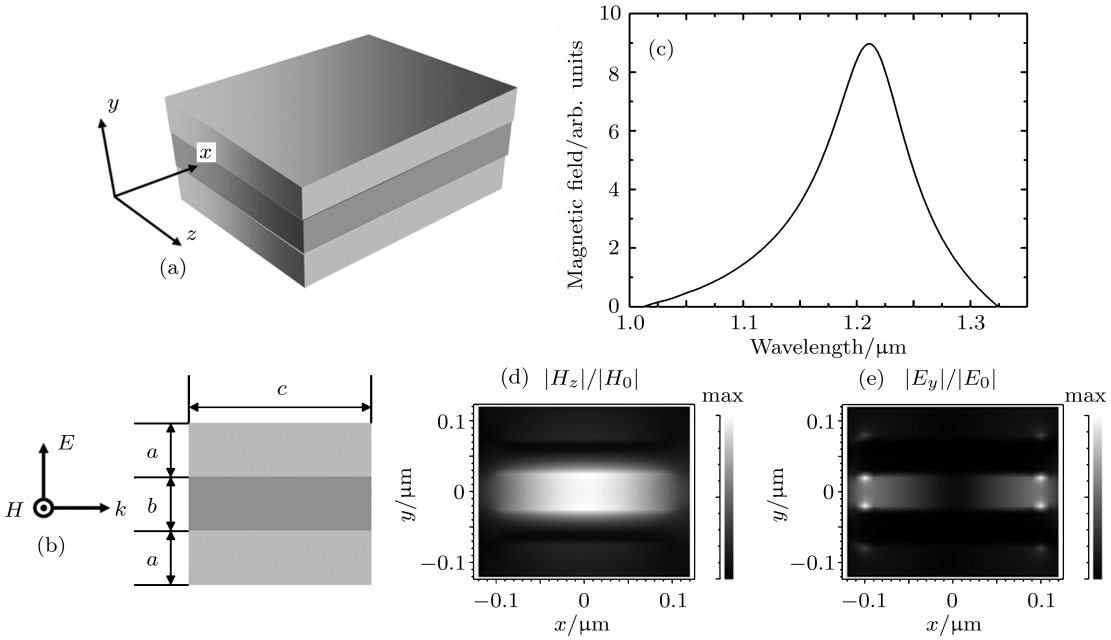


Fig. 1. (a) Geometry of the nanosandwich structure; (b) direction of the external magnetic field; (c) magnetic field in the dielectric layer of the nanosandwich, as a function of wavelength; (d) magnetic field at $z = 0$ plane; (e) the electric field at $z = 0$ plane.

The field intensity distributions calculated by the finite-difference time domain method are shown in Figs. 1(d) and 1(e). When the magnetic resonance happens, the induced currents occur in the two metal layers, and the magnetic field concentrates in the dielectric layer. The magnetic field is shown in Fig. 1(d). The positive and negative charges move to the edges of the two metal layers, which leads to the edge concentration of the electric field (Fig. 1(e)). There exist high order MP modes at higher frequencies. We just focus on the antisymmetric mode[19] in our analysis.

3. Simulated results and analyses

The MP mode resonance wavelength can be tuned by changing the nanosandwich structure parameters: the thickness of the metal layer a, the thickness of the dielectric layer b, the length of the square c, and the refractive index n of the dielectric layer. The nanosandwich structure can be seen as an equivalent resistance–inductance–capacitance circuit. The resistance has no influence on the resonance frequency of the equivalent circuit, so in our study of the resonance frequency, the approximate equivalent circuit can be shown as the circuit in Fig. 2 without any resistance. Points 1 and 2 of the nanosandwich structure in Fig. 2 are separated by the middle dielectric layer to form the equivalent capacitance C_{m}, and the single metal layer can be seen as the equivalent inductance L_{m}. The total equivalent inductance for the straight bar with a rectangular cross section can be expressed as $L = 2L_{\mathrm{m}} \approx A\mu c\left[\ln(2c/\alpha\,(a+c)) - 1\right]$, where $\alpha\,(a+c)$ is the geometric mean distance of the cross section, and $\alpha \approx 0.2235$, and the total equivalent capacitance can be expressed as $C = C_{\mathrm{m}}/2 \approx B\varepsilon\left(c^2/b\right)$, with A and B being the coefficient parameters. To solve the impedance equation of this equivalent inductance–capacitance circuit, the MP mode resonance frequency equation can be expressed as

$$f = \frac{1}{2\pi\sqrt{L_{\mathrm{m}}C_{\mathrm{m}}}} \approx \frac{1}{2\pi\sqrt{AB\dfrac{\mu\varepsilon c^3}{b}\left[\ln(2c/\alpha\,(a+c)) - 1\right]}}. \quad (1)$$

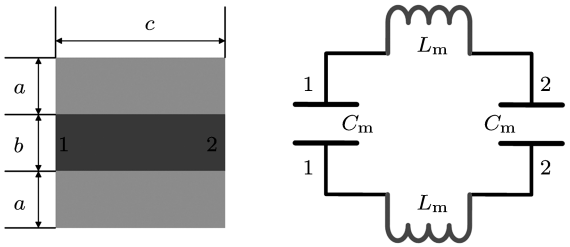


Fig. 2. Equivalent inductance–capacitance circuit of nanosandwich structure.

It can be seen from the frequency in Eq. (1) that the blue shift of the MP mode will occur when the

thickness b increases, and the red shift will appear when the length c and the refractive index n increase. The calculated MP mode resonance wavelength as a function of the dielectric layer thickness b is shown in Fig. 3. For instance, the resonance occurs at the fibre communication wavelengths 1310 nm and 1550 nm, when we fix b values at 23 nm and 12.5 nm, respectively ($a = 50$ nm, $c = 200$ nm, and $n = 1.5$). Based on the resonance frequency equation, the other resonance wavelength required for applications can also be realized by tuning the structure parameters of the nanosandwich.

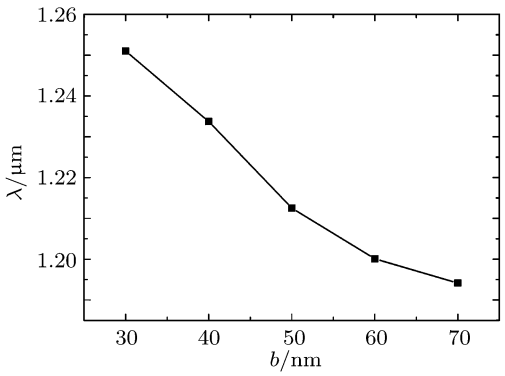


Fig. 3. MP mode resonance wavelength plotted as a function of the thickness b ($a = 50$ nm, $c = 200$ nm, and b varies from 30 nm to 70 nm).

This approximate equation can explain the calculated wavelength shift tendency well. The calculated results, when the other parameters change, can also be illuminated by the approximate equation. The tuning of the nanosandwich structure parameters will lead to the tuning of the values of the equivalent inductance and the equivalent capacitance and finally lead to the wavelength shift. This tuning principle will give guidance on the design of the new waveguides and lasers based on MP modes.

4. Analysis of nanosandwich waveguide

The nanosandwich waveguide is a periodic chain of the single nanosandwich. The configuration of the waveguide scheme is shown in Fig. 4(a). Due to the periodic characteristic of the single nanosandwich in the waveguide, points 1 and 2 in Fig. 4(b) are totally equivalent points. The equivalent circuit of the chain waveguide is shown in Fig. 4(c).

The metal layers of the nearest neighbouring nanosandwiches form the additional capacitance $C_{\rm n}$. By solving the impedance equation

$$\frac{L_{\rm m}\omega {\rm i}}{1 - L_{\rm m}C_{\rm n}\omega^2} - \frac{\rm i}{C_{\rm m}\omega} = 0$$

of this equivalent inductance–capacitance circuit, the MP mode resonance frequency in the nanosandwich waveguide can be expressed as

$$f = \frac{1}{2\pi\sqrt{L_{\rm m}\left(C_{\rm m} + C_{\rm n}\right)}}. \tag{2}$$

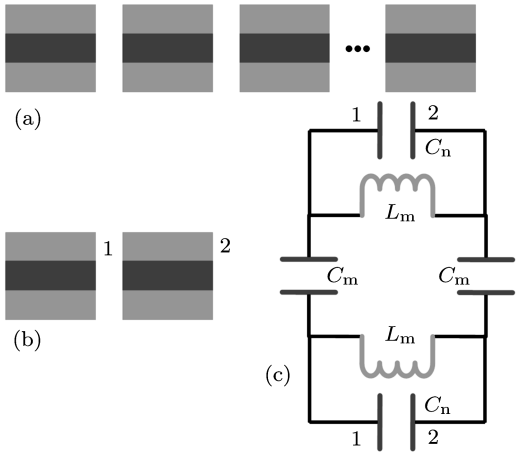


Fig. 4. (a) The geometry of the nanosandwich chain, (b) the two nearest neighbouring nanosandwiches, (c) equivalent inductance–capacitance circuit of nanosandwich waveguide.

For the distribution that is characteristic of MP mode in a nanosandwich and the selected long enough distance between the neighbouring metal slabs in the waveguide model, the value of the capacitance $C_{\rm n}$ is so small that it may be ignored compared with the capacitance $C_{\rm m}$. Hence, the MP mode resonance frequency Eq. (2) in the nanosandwich waveguide can be simplified into $f \approx (1/2\pi\sqrt{L_{\rm m}C_{\rm m}})$. It can be seen from the equation that the resonance frequencies in the nanosandwich waveguide possess almost the same value and change tendency as those of the frequency in the single nanosandwich structure. That is an important reason for the nanosandwich chain to be seen as a waveguide transmitting electromagnetic energy based on the MP mode resonance.

The electromagnetic wave transmission in the chain waveguide is investigated by the finite-difference time domain method. The distance between the nearest neighbouring nanosandwich is 50 nm in the waveguide and the values of other structure parameters

are the same in the calculation. Using continuous wave launch (the resonance wavelength $\lambda = 1212$ nm described in the model and the calculation in the single nanosandwich) with the magnetic field parallel to the middle layer, stable electromagnetic wave transmission can be established in the nanosandwich chain based on the MP modes. The magnetic resonance in every single nanosandwich can be excited by the parallel magnetic resonance in the front sandwich structures. The electromagnetic wave transmission with and without the nanosandwich chain is shown in Fig. 5. It can be seen from Fig. 5(a) that there are forty-one nanosandwiches in the total chain and there is only one nanosandwich at the fourty-first position of the whole chain in Fig. 5(b). A comparison of the energy transmissions shows the function of the nanosandwich chain as a waveguide in condition of the high absorption loss aroused by the metal.

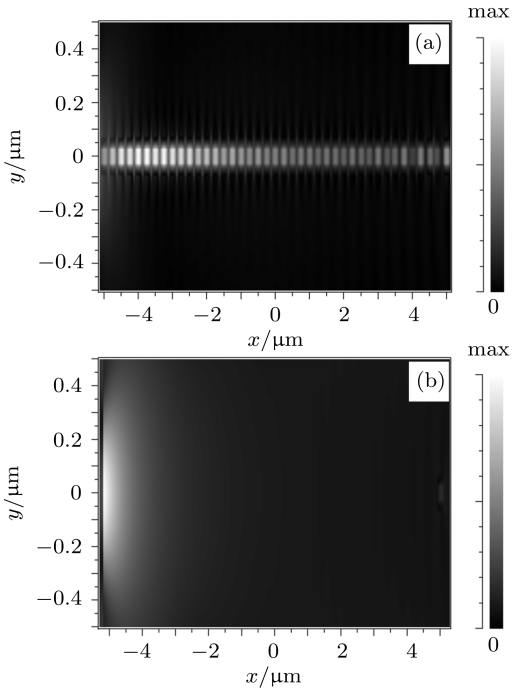


Fig. 5. (a) The electromagnetic wave transmission (Hz intensity) in the nanosandwich waveguide with forty-one nanosandwich units. (b) Transmission without a nanosandwich chain.

In addition, the power transmission in the waveguide is studied. The power transmission efficiency is defined by Eq. (3) to investigate the power flow through the waveguide, as a function of time. The $E(t)$ and the $H(t)$ are the electric and the magnetic fields and S_0 is the launch power. The integral is evaluated over an area A (a little bigger than the cross sectional area of a single nanosandwich middle dielectric layer in the transmit direction) normal to the transmit direction.

$$S(t) = \frac{\mathrm{Re}\left[\int_A [E(t) \times H^*(t)] \cdot \mathrm{d}\boldsymbol{A}\right]}{S_0}. \tag{3}$$

Figure (6) shows the power transmissions at different ports of the nanosandwich unit. The power flows in units 6, 11, 16, 21, and 26 each can reach a certain stable transfer rate after tens of time ct. The stable power flows at different ports of the waveguide suggest that the energy transmission based on MP resonance is established in the nanosandwich waveguide.

Then we analyse the power transmission of such a nanosandwich waveguide using gold and silver as the metal layers. It can be seen from Fig. 7 that the nanosandwich waveguide using silver material possesses a higher power transmission efficiency. That is because the higher conductance of silver will lead to a lower absorption loss aroused by the metal. The maximal power transmission efficiency of a silver nanosandwich chain is 0.546, and it is 0.523 for the gold chain at the fifth port of the nanosandwich waveguide.

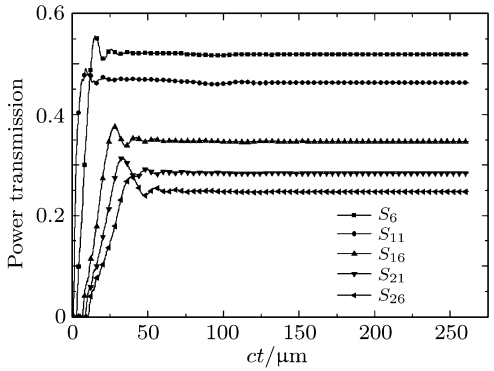


Fig. 6. Power transmission of the nanosandwich waveguide (c is the velocity of light, and t is the transmission time of the power flow).

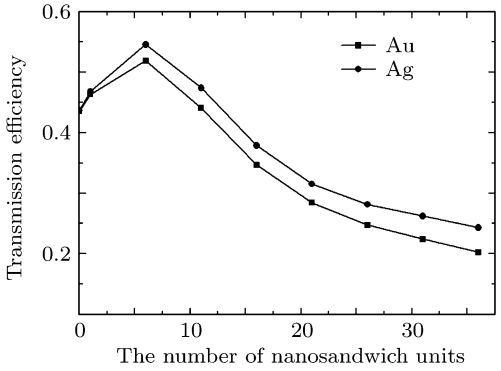


Fig. 7. Power transmission efficiencies for different numbers of unit cells.

The increase in the transmission efficiency is enhanced mainly by the magnetic resonance in the nanosandwich structure when the total number of nanosandwich units is less than 5. The decrease in the transmission efficiency is aroused by the absorption loss when the total number of nanosandwich units is more than 5. We can see from the power transmission curve in Fig. 7 that the magnetic resonance in the nanosandwich structure enhances the energy transmission in the chain waveguide, and for such a waveguide the power transmission efficiency will reach a maximal value at a certain number of nanosandwich units. The optimal power transmission efficiency is determined by the MP mode resonance enhancement and the absorption loss aroused by the metal material in such a waveguide.

5. Summary

An equivalent inductance capacitance circuit analysis method is proposed to illuminate the MP mode resonance in the nanosandwich structure and the nanosandwich chain waveguides. The metal absorption loss is high in the nanosandwich structure. However, the nanosandwich chain waveguide can reach a relatively high power transmission efficiency enhanced by the magnetic resonance in the waveguide nuit, and the waveguide can transmit electricmagnetic energy tightly on the nanometer scale, far beyond the diffraction limit. Due to the loss characteristic of the metal material, gain materials, such as quantum well and quantum dot materials, can be chosen as the middle dielectric layer to compensate for the high losses and keep the devices working stably based on MP mode. The advantage of MP mode will give guidance and possibility in the realization of ultracompact optoelectronic devices.

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