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Enlargement of the band gap in the metal–insulator–metal heterowaveguide

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A B S T R A C T

We present a new metal–insulator–metal (MIM) heterowaveguide to enlarge the band gap, which is formed by alternately stacking two kinds of metals, modulating the MIM waveguide slit, and inserting different dielectric materials with the effective refractive index periodically modulated. Based on this structure, we adopt two different methods to enlarge the band gap: changing the thickness of the unit layer and combining two MIM structures. Both of them widen the band gap when surface plasmon polaritons propagate through the structure. This metal heterostructure is expected to have applications in surface plasmon polaritons (SPPs) based optical devices, such as filters, waveguides, especially for broad band gap elements.

1. Introduction

Surface plasmon polaritons (SPPs) are quasi-particles resulting from the coupling of electromagnetic waves with oscillations of conduction in a metal and propagate along the interface between a dielectric and a noble metal with amplitudes decaying into both layers. One of the most attractive aspects of the SPPs is that they can be used to overcome the diffraction limit. This leads to miniaturized photonic devices with scales much smaller than those currently achieved. Recently, various kinds of optical devices, such as waveguides, reflectors, filters as well as beam splitters, have been proposed [1–5].

As a most fundamental photonic device, the waveguide structures have been investigated theoretically and experimentally. Recently, Wang et al. reported a planar metal heterowaveguide constructed by alternately stacking two kinds of metal gap waveguide with periodically modulated effective refractive index, leading to SPPs band gap structure [3]. Hosseini and Massoud proposed a low-loss plasmonic Bragg reflector consisting of alternatively stacked metal–insulator–metal (MIM) waveguide with different dielectric materials [6]. Han and He devised the surface plasmon Bragg grating formed by a periodic variation of the width of the insulator in a MIM waveguide [7]. Liu et al. investigated a wide band gap Bragg reflector by modulating the MIM waveguide slit and inserting dielectric materials with higher refractive index in the grating sections with narrow slit width [8]. From these it shown that there are three facets which can effect the refractive index, but all the above works modulated one or two facets to enlarge the band gap.

In the other hand, since the photonic crystals (PCs) can efficiently control the propagation of the electromagnetic wave, they have attracted tremendous interest in recent years and have been applied in many aspects, such as filters, wave guides, optical switches, diode laser, photon polarization spectroscopy [9–13]. Wang et al. demonstrated that it was possible to enlarge the total reflection frequency range by combining two or more photonic crystals [14]. This method can also be used in MIM heterowaveguide to widen the SPPs-based band gap.

In this work, we will present a new MIM heterowaveguide structure with large band gap. We show that alternately stacking two kinds of metal, modulating the MIM waveguide slit, and inserting different dielectric materials with periodically modulated refractive index, can enlarge the band gap. Based on this structure, we adopt two methods to enlarge the band gap: changing the thickness of the unit layer or combining two MIM structures. The transfer matrix method (TMM) is utilized to investigate the characteristics of the band gap [15].

2. The MIM waveguide structure and effective refractive index

The MIM waveguide is a planar metallic waveguide with two semi-infinite metal walls and the middle layer between two walls is a dielectric film with width w, as shown in Fig. 1a. When the width of dielectric layer is reduced below the diffraction limit, conventional guiding modes cannot exist. In this case, a TM polarized

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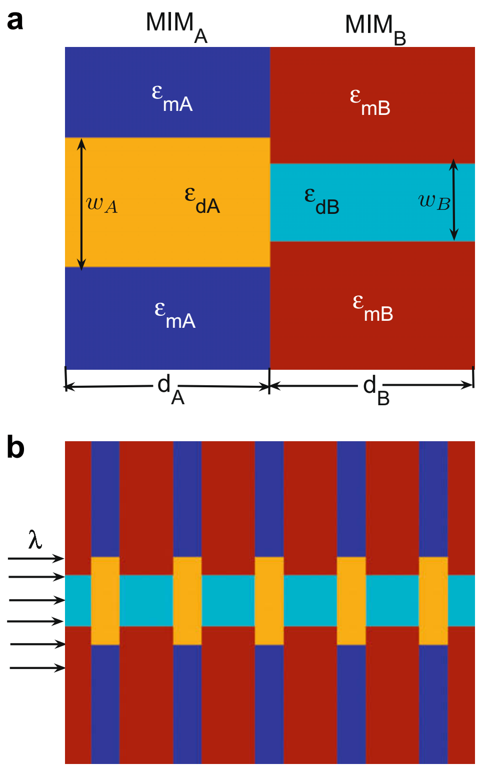

Fig. 1. (a) Scheme of a unit cell of two combined MIM heterowaveguides, where MIM_A is structure Au–SiO_2–Au, with slit width and thickness of w_A and d_A; MIM_B is structure Al–$PSiO_2$–Al, with slit width and thickness of w_B and d_B. (b) Schematic of periodic heterostructure composed of MIM_A and MIM_B waveguides, alternatively.

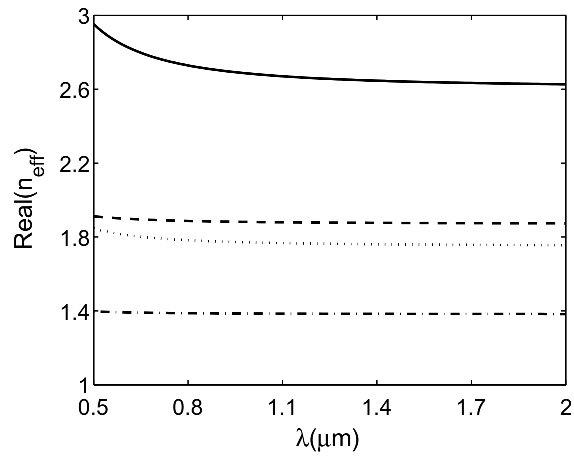

Fig. 2. Variation of the real part of n_{eff} with wavelength for SPPs modes in the MIM waveguides. The solid line and dot line are corresponding to MIM_A with $w = 20$ nm and $w = 100$ nm. The dash line and dot-dash line are corresponding to MIM_B with $w = 20$ nm and $w = 100$ nm.

incident light will be transformed into the coupled SPPs on the metal surfaces and propagates along the waveguide. The dispersion relation of the SPPs in the MIM waveguide can be deduced from the Maxwell equations as

$$\frac{p\varepsilon_d}{k\varepsilon_m} = \frac{1 - e^{kw}}{1 + e^{kw}}, \tag{1}$$

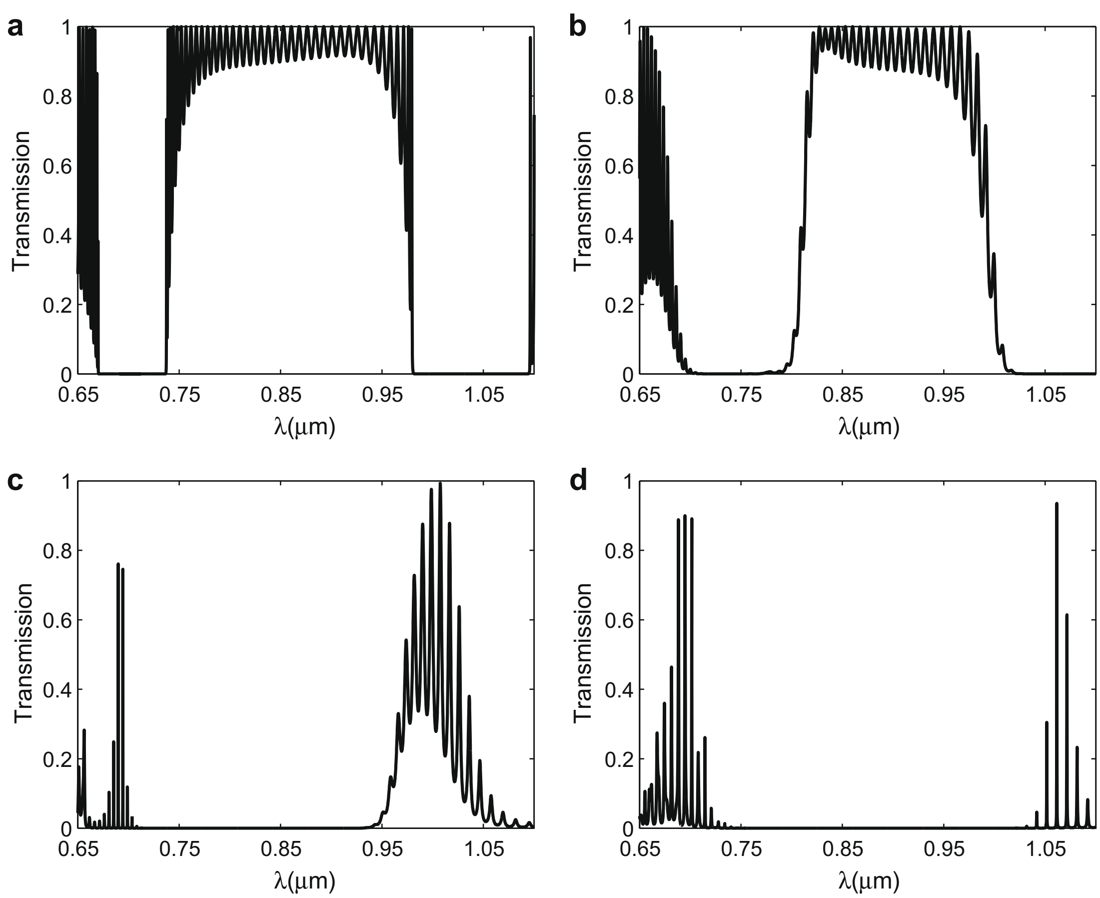

Fig. 3. Transmission spectrum of: (a) the structure H, (b) modulated structure H_B, (c) modulated structure H_A, and (d) modulated structure H_{AB}.

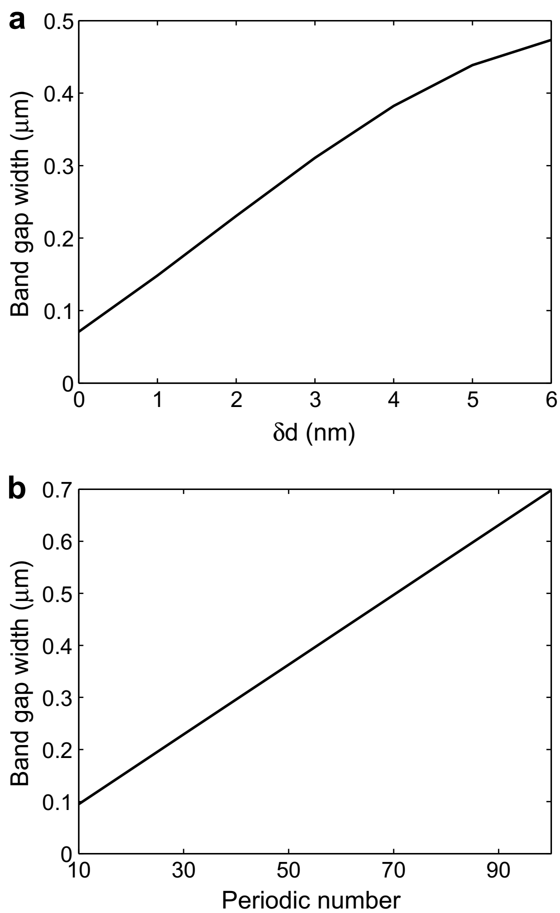

Fig. 4. Dependence of the width of the band gap on: (a) the varying step δd when the periodic number is selected $m = 40$, and (b) on the periodic number m when the step $\delta d_A = \delta d_B = 3$ nm.

where

$$k = k_0\sqrt{\left(\frac{\beta_{SPP}}{k_0}\right)^2 - \varepsilon_d}; \tag{2a}$$

$$p = k_0\sqrt{\left(\frac{\beta_{SPP}}{k_0}\right)^2 - \varepsilon_m}, \tag{2b}$$

and

$$\beta_{SPP} = n_{SPP}k_0, \tag{3}$$

where k_0 is the wave vector in free space, β_{SPP} and n_{SPP} are the complex propagation constant and the effective refractive index of SPPs, respectively. ε_m and ε_d are the relative dielectric constant of the metal and the dielectric material, respectively. The relative dielectric constant ε_m is from the Drude formula

$$\varepsilon_m = \varepsilon_\infty - \frac{\omega_p^2}{\omega(\omega + i\gamma)}, \tag{4}$$

where $\epsilon_\infty = 1.0$. Two kinds of MIMs are constructed. MIM_A is composed of materials Au with $\omega_p = 1.37 \times 10^{16}$ Hz, $\gamma = 1.52 \times 10^{12}$ Hz and SiO_2 with refractive index $n_d = 1.46$. MIM_B is composed of materials Al with $\omega_p = 2.28 \times 10^{16}$ Hz, $\gamma = 1.52 \times 10^{12}$ Hz and $PSiO_2$ with refractive index $n_d = 1.23$ [8,16]. Fig. 2 shows the real part of the effective refractive index versus the wavelength for the fundamental TM mode in the MIM waveguides. It can is found that for different MIM waveguides the effective refractive index can be changed by selecting different dielectrics, metals, or the widths of dielectric.

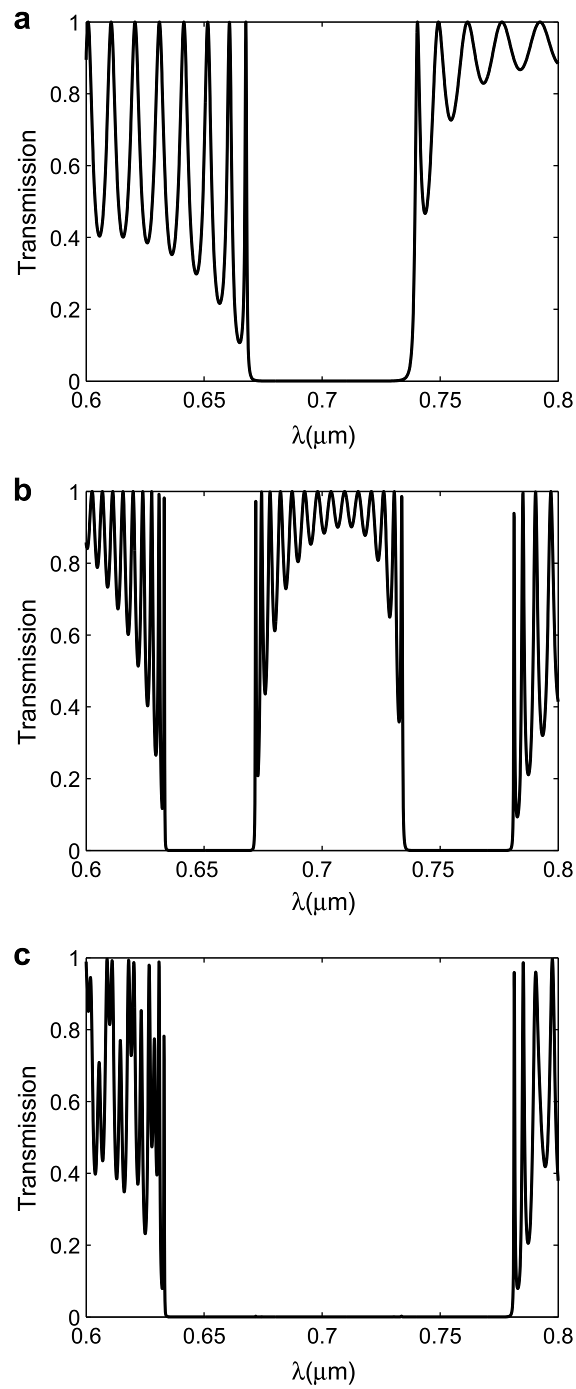

Fig. 5. Transmission spectra of: (a) structure H_1, (b) structure H_2, and (c) combined structure H_1/H_2.

Analogous to one dimensional grating, we stack the above MIM heterowaveguide periodically, as shown in Fig. 1b, to achieve different devices.

3. Enlargement of the band gap

Generally, greater refractive index contrast of two adjacent layers is adopted to achieve a broader band gap. Thus the structures Au–SiO_2–Au and Al–$PSiO_2$–Al are selected as $MIM_A(A)$ and $MIM_B(B)$, respectively. The width of SiO_2 is $w_A = 20$ nm in MIM_A and the width of $PSiO_2$ is $w_B = 100$ nm in MIM_B. By alternately stacking the $MIM_A(A)$ and $MIM_B(B)$ layer, a metal waveguide heterostructure $H((AB)^p)$ with thickness of $d_A = 0.26a$ and $d_B = 0.74a$ can be achieved, where $a = 0.60$ μm is the lattice constant of the structure. For $p = 40$, the transmission spectrum of this structure for is shown in Fig. 3a. It can be clearly seen that there is a band gap in the range of [0.670–0.737] μm.

The band gap can be effectively enlarged by adjusting the thickness of each layer. Based on the structure H, the thicknesses of the layers A and/or B can be modulated to generated a thickness gradually changed structure $(A_nB_n)^m$, where m is the periodic number of the structure and $n = 1, 2, \ldots, m$. The thickness of the nth $A(B)$ layer is changed into $(d_{A(B)})_n = d_{A(B)} + n\delta\, d_{A(B)}$. If $\delta d_{A(B)} = 0$, the structure is just as the heterostructure H. In order to enlarge the band gap, different methods are adopted in this work. Firstly, the thicknesses of A layers keep invariable, only the thicknesses of B layers are increased with a step $\delta d_B = 3$ nm to construct a new structure H_B. The transmission spectrum of this structure is shown in Fig. 3b. The band gap has been widened to [0.699–0.788] μm. Secondly, the thicknesses of A layers are increased with a step δd_A, while the thicknesses of B layers keep invariable to form another structure H_A. The transmission spectrum of H_A is shown in Fig. 3c. The band gap range is [0.704–0.942] μm which is much wider than that of original structure H. The band gap width can be further enlarged by changing the thicknesses of A and B layers simultaneously. The generated structure is named as H_{AB}. In this case, the transmission spectrum is presented in Fig. 3d with the band gap in the range of [0.731–1.042] μm. It demonstrates that the band gap have been broaden effectively. Since the thickness of layers A or B is gradually changed, the structure forms a chirped Bragg grating [17], thus the effective band gap has been enlarged. The dependence band gap widths on the parameters δd and m are shown in Fig. 4a and b, respectively. It is noted that the band gap width increases with respect to δd or m.

The band gap can also be enlarged by combining two heterostructures H_1 and H_2. H_1 and H_2 are composed of MIM_B and MIM_B with $d_A = qa$ and $d_B = (1 - q)a$. The parameters for H_1 are $a = 0.60$ μm and $q = 0.26$ and $a = 1.0$ μm, $q = 0.633$ for H_2. The transmission spectra of H_1 and H_2 are shown in Fig. 5a and b, respectively. The band gaps are [0.670–0.737] μm for H_1 and [0.632–0.671] μm and [0.733–0.779] μm for H_2. Combining H_1 and H_2, an enlarged band gap is obtained. The corresponding transmission spectrum is shown in Fig. 5c. Due to the overlap of the band gaps for H_1 and H_2, the band gap of the combined structure H_1/H_2 is [0.632–0.779] μm, which is much larger than that of H_1 or H_2.

4. Summary

In summary, we have presented a new type of metal waveguide heterostructure constructed by MIM. By changing the thickness of MIM_A or MIM_B in the structure, the band gap is enlarged effectively. We can also achieve a wide band gap by stacking two heterowaveguides together. These metal waveguide heterostructures are expected to have application in SPP-based optical devices, especially for broad band gap elements.

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