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Theoretical study of ultra-wideband slow light in dual-stub-coupled plasmonic waveguide

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ABSTRACT

We propose and demonstrate a metal-insulator-metal (MIM) waveguide side coupled double stubs to realize broadband slow surface plasmon polaritons (SPPs) around the telecom frequency 193.5 THz. When the depth of single stub is approximately equal to integral multiple of half plasmon wavelength, owing to the constructive interferences between the electromagnetic wave propagating through the MIM waveguide and that reflected from the stubs, wideband slow light effect appears. The improved transmission line theory calculation indicates that the group velocity of SPPs in the plasmonic waveguide system for stub depth 1111 nm is 0.1*c* (*c* is light speed in vacuum.) over a broad bandwidth of 69 THz. Exploiting the finite-difference time-domain (FDTD) numerical simulation, the group velocity of pulse for width 20 fs (Full width at half high) is calculated. The result agrees well with that predicted by the transmission line theory. This plasmonic waveguide for slow light effect has important potential application in optical delay lines.

1. Introduction

Recently, slow light has attracted tremendous interest because of its potential applications in optical buffers, optical memories, optical communications, and nonlinear optics. Until now, several technologies, such as the electromagnetically induced transparency (EIT) [1], the coherent population oscillation [2], stimulated Brillouin scattering [3], photonic crystal waveguides [4] and plasmonic waveguides [5], have been demonstrated to achieve slow light effect. The surface plasmon polaritons (SPPs) shows promising prospect in the field of slow light effect owing to exhibiting sub-wavelength confinement of electromagnetic field in the direction perpendicular to a conductor-dielectric interface [5–14].

The frequency bandwidth is one of important optical properties for slow light device [15]. Recently, wideband slow light phenomenon has been researched in plasmonic waveguides [16–18]. For example, Zafar, R. et al. investigated the slow light characteristic of SPP modes around the frequency 210 THz by introducing double stub resonators in MIM plasmonic waveguides, and an ultra large bandwidth of 21 THz was obtained [16]. Lin. W. et al. proposed and demonstrated an plasmonic superlattice, consisting of a two-dimensional metal gap waveguide inserted with thin metal films working as coupled reflectors, to realize slow light effect on a broad bandwidth of 37 THz [17]. The MIM waveguide side coupled with stubs [18,19] or a series of the slots cavity [20] has proposed to demonstrate slow light effect. By appropriately adjusting the distance between the two stubs of a unit cell, a flat band corresponding to nearly constant group index over a broad bandwidth of 8.6 THz can be achieved [18].

In this paper, we investigate the MIM waveguide side coupled double stubs to illustrate slow light phenomenon around the telecom frequency 193.5 THz. Working bandwidth of the slow light device is 69 THz. Wideband slow light effect appears owing to the constructive interferences between the electromagnetic wave propagating through the MIM waveguide and that reflected from the stubs. In addition, the normalized delay-bandwidth product (NDBP) of this waveguide system is calculated as high as 3.24, implying a high slow light capacity. Moreover, the structure of plasmonic device is simple and fabricated easily.

The rest of this paper is arranged as follows. In Section 2, we propose the plasmonic device and give the model by the improved transmission line theory. In Section 3, we discuss the transmission, dispersion and group velocity, and obtain the stable slow group velocity over broad frequency ranges. A conclusion is given in Section 4.

2. Structure model and theory

The schematic diagram is shown in Fig. 1(a). There is a metal-insulator-metal (MIM) waveguide side coupled with double stubs

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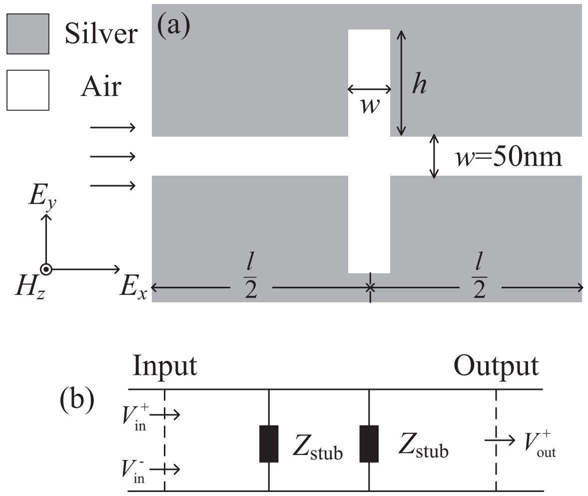

Fig. 1. (a) Schematic of the MIM plasmonic waveguide system: $w = 50$ nm, the dielectric gap width of the waveguide and stubs; $l = 200$ nm, is the length of plasmonic structure; h is depth of each stub. The TM-polarization light vertically illuminates the structure from the left side. (b) The transmission line model of the MIM plasmonic waveguide system. Z_{Stub} is the effective impedance of each stub.

(upper stub and down stub). The deep of each stub is the same ($=h$). The length of MIM waveguide in x coordinate axis is $l = 200$ nm. The core layer width of the stub and MIM waveguide is $w = 50$ nm. The core layer is air and the metal cladding layer is silver. The frequency-dependent relative dielectric constant of silver is described by Drude model [21]:

$$\varepsilon_{\text{m}} = \varepsilon_{\infty} - \omega_{\text{p}}^{2}/\left(\omega^{2} + i\omega\gamma\right), \tag{1}$$

where ε_{∞}, caused by the inter-band transition, is dielectric constant at infinite frequency, ω_{p} is bulk plasma frequency, and γ is electron collision frequency. According to Ref. [21], $\varepsilon_{\infty} = 3.7$, $\omega_{\text{p}} = 1.38 \times 10^{16}$ rad/s, $\gamma = 2.73 \times 10^{13}$ rad/s. The relative dielectric constant of air ε_{air} equals to 1. When the electromagnetic wave of the frequency 193.5 THz incidents into the MIM waveguide, the cut width of TM_1 model is about 627 nm. Therefore, there is only the TM_0 model in our discussed plasmonic waveguide system due to small width of insulator layer.

The transmission and dispersion properties for the plasmonic waveguide system are investigated by an improved transmission line model [6,22]. The double-stub structure can be expressed as a transmission line with two stubs [23], as shown in Fig. 1(b). The proposed waveguide system is equivalent to a parallel connection of an infinite transmission line (representing the MIM waveguide) and a serial finite transmission line (representing the stub). The characterized impedance of infinite transmission line is given by

$$Z_{\text{MIM}} = \beta w/\omega\varepsilon_0\varepsilon_{\text{air}}, \tag{2}$$

where, β, ω and ε_0 are propagation constant of SPPs in MIM waveguide, angle frequency and dielectric constant in vacuum, respectively. The characterized impedance $Z_{\text{S}} = \beta w/\omega\varepsilon_0\varepsilon_{\text{air}}$ of finite transmission line is terminated by a load $Z_{\text{L}} = \sqrt{\epsilon_{\text{m}}/\epsilon_{\text{air}}}Z_{\text{S}}$. Therefore, effective characterized impedance of finite transmission line (*i. e.* the upper and down stub) has the form

$$Z_{\text{Stub}} = Z_{\text{S}}\frac{Z_{\text{L}} - iZ_{\text{S}}\ \tan(\beta h)}{Z_{\text{S}} - iZ_{\text{L}}\ \tan(\beta h)}. \tag{3}$$

Thus, the transfer matrix of our proposed waveguide system can be described as

$$m = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix} = A\left(\frac{l}{2}\right)B\left(Z_{\text{Stub}}\right)B\left(Z_{\text{Stub}}\right)A\left(\frac{l}{2}\right) \tag{4}$$

with the expressions of $A(l/2)$ and $B(Z_{\text{Stub}})$ having the form

$$A\left(\frac{l}{2}\right) = \begin{pmatrix} \exp\left(-i\beta\frac{l}{2}\right) & 0 \\ 0 & \exp\left(-i\beta\frac{l}{2}\right) \end{pmatrix} \tag{5}$$

and

$$B\left(Z_{\text{Stub}}\right) = \begin{pmatrix} 1 + \dfrac{Z_{\text{MIM}}}{2Z_{\text{Stub}}} & \dfrac{Z_{\text{MIM}}}{2Z_{\text{Stub}}} \\ -\dfrac{Z_{\text{MIM}}}{2Z_{\text{Stub}}} & 1 - \dfrac{Z_{\text{MIM}}}{2Z_{\text{Stub}}} \end{pmatrix} \tag{6}$$

respectively. The transmission coefficient $t = t_{\text{R}} + it_{\text{I}}$ and transmission can be obtain by

$$t = t_{\text{R}} + it_{\text{I}} = 1/m_{11} \tag{7}$$

and

$$T = |t|^2 \tag{8}$$

dispersion relation of SPPs can be given as [24]

$$Kl = \tan^{-1}\left(t_{\text{I}}/t_{\text{R}}\right) \tag{9}$$

with K and l being wave vector of SPPs and the total length of the plasmonic waveguide system, respectively. The group velocity is defined as

$$v_{\text{g}} = \text{d}\omega/\text{d}K. \tag{10}$$

3. Numerical results and discussions

When the electromagnetic wave of 193.5 THz propagates through the plasmonic structure, using the improved transmission line theory, the transmission as a function of the stub deep h is obtained. The results are shown in Fig. 2. The transmissions reach to the maximum at the stub deep 547, 1111, 1674 and 2238 nm, while those reach to the minimum at 266, 829, 1393, 1957 nm. The transmission characteristic varies periodically with the stub deep, which originates from the destructive or constructive interferences between the electromagnetic wave propagating through the MIM waveguide and that reflected from the stubs [23]. Under

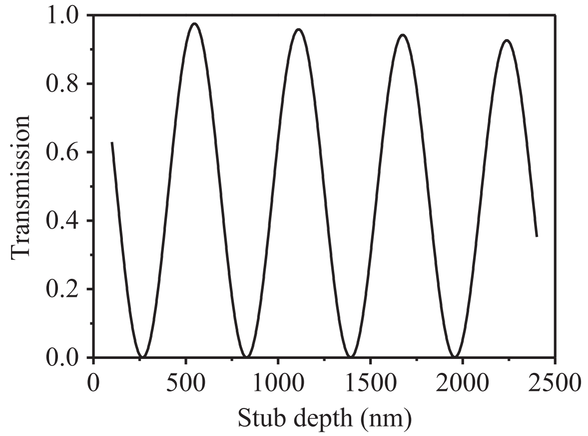

Fig. 2. Transmission characteristics as a function of the stub deep for the MIM waveguide coupled with double stubs. The incident wavelength is fixed at 1550 nm.