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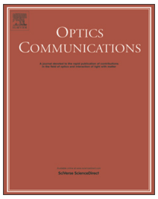

Wideband slow light based on plasmon-induced transparency at telecom frequency

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ABSTRACT

We propose and demonstrate a metal–insulator–metal (MIM) waveguide side coupled with a series of stubs to realize broadband slow surface plasmon polaritons (SPPs) around the telecom wavelength 193.5 THz. The obviously slow light effect results from the strong normal dispersion around the frequency of the plasmon-induced transparency. Theoretical calculations indicate that the plasmonic waveguide system of the length 11 μm works on a broad bandwidth of 20 THz. The group velocity of SPPs predicted by the improved transmission line theory is about 0.2*c* (*c* is light speed in vacuum), which is confirmed by the finite-difference time-domain (FDTD) numerical simulation. The waveguide system for slow light effect has important potential application in optical delay lines.

1. Introduction

Slow light, showing its remarkable ability to reduce group velocity, has attracted great interest because of its potential applications in optical buffers, optical memories, optical communications, and nonlinear optics. Slow light can be realized by the following technologies [1–7]: the electromagnetically induced transparency (EIT) [1], the coherent population oscillation [2], stimulated Brillouin scattering [3], photonic crystal waveguides [4,5] and plasmonic waveguides [7]. The surface plasmon polaritons (SPPs) exhibit subwavelength confinement of electromagnetic field in the direction perpendicular to a conductor–dielectric interface [8] and show promising prospect in the fields of waveguide devices [9,10], biomedical sensing [11,12], slow light effect [13,14], and so on.

The slow group velocity of SPPs has been discussed in superlattice [13–19], metal–insulator–metal [20–22], and graded insulator (or metal) grating waveguide [23–25]. Recently, EIT-like spectrum was researched in MIM waveguide side coupled with stubs to achieve slow light transmission [26–28]. For example, Han theoretically demonstrated dual-channel slow light around the induced-transparency frequencies of 283 and 310 THz [27]. Zafar 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 [28].

In this paper, we investigate the analog of EIT in MIM waveguide perpendicularly side coupled with stubs to illustrate slow light effect around the telecom frequency 193.5 THz. The smooth and flat dispersion curve reveals a slow group velocity over the broad bandwidth of 20 THz.

The rest of this paper is arranged as follows. In Section 2, we discuss the transmission of the MIM waveguide side coupled with one stub, and determine the structure and geometry size of a unit cell. In Section 3, we research the slow light effect of the MIM waveguide side coupled with *N* unit cells. A conclusion is given in Section 4.

2. Theory model and structure design

The schematic diagram is shown in Fig. 1(a). There are two stubs that are side coupled to metal–insulator–metal (MIM) waveguide in each unit cell. The height of stubs in each unit cell is h_1 and h_2, respectively. N denotes period number of unit cell. The width of the stub and core layer in MIM waveguide is $w = 100$ 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 [29]

$$\varepsilon_m = \varepsilon_\infty - \omega_p^2 / \left(\omega^2 + i\omega\gamma\right), \tag{1}$$

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. [29], $\varepsilon_\infty = 3.7$,

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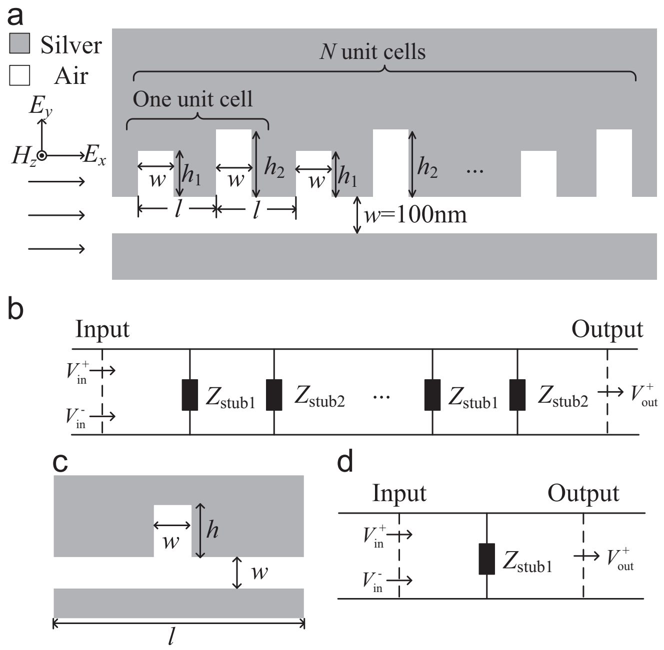

Fig. 1. (a) Schematic of the MIM plasmonic waveguide system: $w=100$ nm, the dielectric gap width of MIM waveguide and stubs; $l=550$ nm, the distance between the two stubs in each unit cell; $2l$ is the length of each unit cell; h_1 and h_2 are depths of two stubs in each unit cell, respectively. The TM-polarization light vertically illuminates the structure from the left side. (b) The transmission-line model of the MIM plasmonic waveguide system. Z_{Stub1} and Z_{Stub2} are the effective impedances of two stubs in each unit cell. (c) Schematic of the MIM plasmonic waveguide with one stub: $w=100$ nm, the dielectric gap width of MIM waveguide and stub; h and $l=550$ nm, the depth of the stub and the length of the MIM plasmonic waveguide, respectively. (d) The transmission-line model of the MIM plasmonic waveguide with one stub. Z_{Stub} is the effective impedance of the stub.

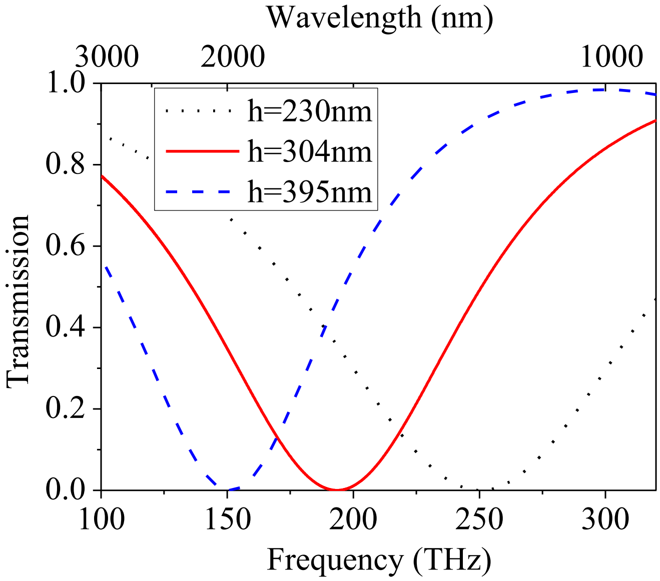

Fig. 2. Transmission spectrum of MIM waveguide side coupled with one stub for different stub depth h with $l=550$ nm and $w=100$ nm.

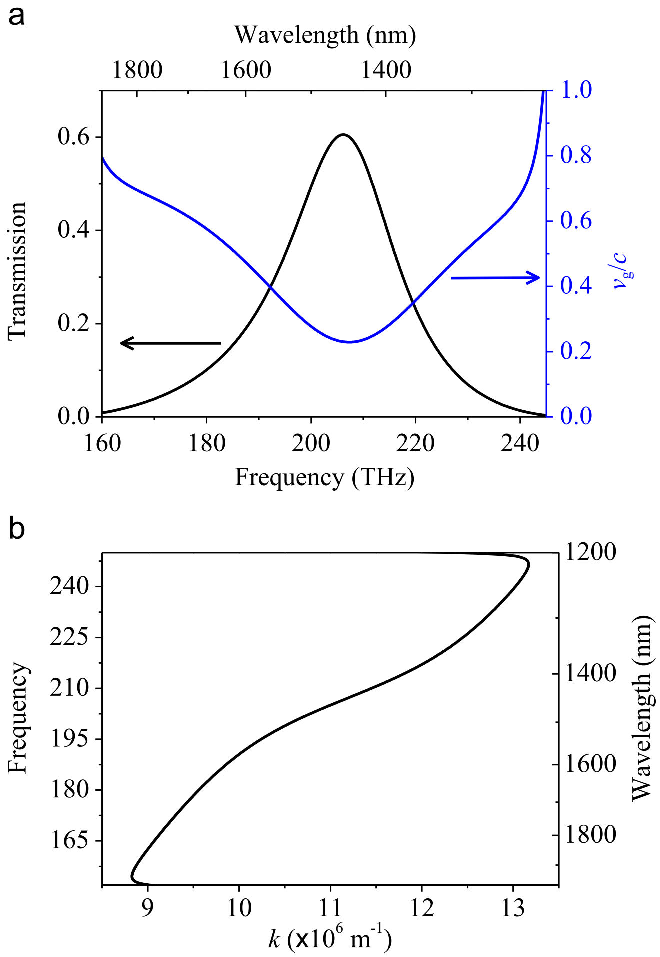

Fig. 3. MIM waveguide side coupled one unit cell (i.e. $N=1$), $l=550$ nm, $h_1=230$ nm and $h_2=395$ nm: (a) transmission spectrum and group velocity of SPP, c is the light speed in vacuum; and (b) dispersion curve.

$\omega_p = 1.38 \times 10^{16}$ 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 the small width of insulator layer.

We use an improved transmission model to investigate the transmission properties of the plasmonic waveguide system [27,30]. According to the transmission line theory, our 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 $Z_S = \beta w / \omega \varepsilon_0 \varepsilon_{\text{air}}$ of finite transmission line is terminated by a load $Z_L = \sqrt{\varepsilon_m / \varepsilon_{\text{air}}} Z_S$. Therefore, effective characterized impedance of finite transmission line (i.e. the stub) has the form

$$Z_{\text{Stub1,2}} = Z_S \frac{Z_L - iZ_S \tan(\beta h_{1,2})}{Z_S - iZ_L \tan(\beta h_{1,2})}. \tag{3}$$

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

$$m = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix} = \left[A\left(\frac{l}{2}\right) B(Z_{\text{Stub1}}) A(l) B(Z_{\text{Stub2}}) A\left(\frac{l}{2}\right) \right]^N \tag{4}$$

with the expressions of $A(l/2)$ and $B(Z_{\text{Stub1,2}})$ having the form