Optics Communications 290 (2013) 188–191

Contents lists available at SciVerse ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Rainbow trapping of surface plasmon polariton waves in metal–insulator–metal graded grating waveguide

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ARTICLE INFO

Article history:
Received 25 September 2012
Received in revised form
10 October 2012
Accepted 12 October 2012
Available online 30 October 2012

Keywords:
Surface plasmon polaritons
Photonic integrated circuits
Graded grating waveguides
Finite-difference time-domain

ABSTRACT

A new metal–insulator–metal (MIM) graded grating waveguide, based on surface plasmon polaritons (SPPs), is proposed and numerically investigated to realize the rainbow trapping of SPP waves. We find that the localized positions of SPP waves depend on the frequencies of the incident light. The theoretical results show that the trapping time of SPP waves can be up to 83.4 fs and the proposed compact configuration can be operated in a broad bandwidth of 90 THz. Our MIM graded grating waveguide may find significant applications on plasmonic slow-light systems, especially chip-based optical buffers and spectrometers.

1. Introduction

Surface plasmon polaritons (SPPs) are waves that propagate along the surface of a conductor due to the interaction between the light waves and the free electrons of the conductor, usually a metal [1,2]. SPPs are considered as one of the most promising methods for concentrating and channeling light at nanoscale due to their ability to overcome the traditional diffraction limit [3,4]. By altering the structure of a metal's surface, the properties of SPPs can be tailored, which offers great potential for developing new types of photonic integrated circuits at nanoscale [5–7]. In recent years, a lot of devices based on SPPs have been investigated both theoretically and experimentally, such as reflectors [8,9], wavelength demultiplexers [10,11], absorbers [12], couplers [13], filters [14–16], splitters [17] sensors [18], plasmonic lens [19], and all-optical switching [20].

Slow light with a remarkably reduced group velocity offers the possibility for time-domain processing of optical signals. It can find potential applications in optical memory [21], information storage [22], and optical buffers [23]. Rainbow trapping effect, an interesting and meaningful plasmonic slow-light phenomenon, is first proposed by Tsakmakidis et al. [24] and has been widely investigated in recent years [25–33]. For instance, Gan et al. have already investigated the rainbow trapping effect on surface structures in different frequencies domain, both theoretically and experimentally, such as telecommunication domain [25], visible domain [26,27] as well as THz domain [28–30], and specially reported the experimental verification of the rainbow trapping effect in adiabatic plasmonic gratings [31]. In addition, He et al. have theoretically revealed the truth about 'trapped rainbow' storage of light in metamaterials that the complete standstill of light at the critical thickness is impossible, which is also verified experimentally [32]. However, the previous researches mainly focus on how to realize slowing and trapping light on the metal surface [25–34], which may result in large scattering loss due to the poor confinement of light. That MIM rainbow trapping structures are superior to others in terms of trapping performance has been demonstrated in Ref. [35]. So it is important to investigate how to trap light in MIM plasmonic waveguides, which have better confinement of light and acceptable propagation length [36–40].

In this paper, a MIM graded grating waveguide is proposed and numerically investigated by using finite-difference time-domain (FDTD) method and transmission line theory [41]. Compared with the article Ref. [33], we utilize the transmission model to analysis the dispersion relation of the MIM graded grating waveguide and especially discuss the trapping time of SPP waves in detail. The theoretical and simulated results show that the group velocity of the incident light can be significantly slowed down in the proposed structure. We also find that the localized positions of SPP waves are dependent on the frequencies of the incident light. Compared with the previous reports, our structure shows better confinement and longer trapping time of SPP waves. In addition, the proposed structure can be operated in a broad bandwidth of 90 THz. This plasmonic configuration may find important potential applications on plasmonic slow-light systems, especially chip-based optical buffers and spectrometers.

2. Structure model and theory

Fig. 1 shows the schematic diagram of the proposed graded grating waveguide. The structure consists of a MIM waveguide

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0030-4018/$ - see front matter
http://dx.doi.org/10.1016/j.optcom.2012.10.020

periodically coupled with series of the graded stubs. The upper and lower graded stubs can form two different graded gratings. Compared with the metallic surface structure of Ref. [28], our MIM waveguide, the so-called sandwich structure, not only has better energy confinement of SPP waves and highly compact structure but also performs excellent optical properties, which are better than the previous investigations about slow light on the metal surface.

When a TM-polarized plane wave is coupled into the waveguide, SPP waves can be excited at the metal–insulator interfaces and confined in the insulator layer. The metal in our structure is selected as silver, whose frequency-dependent relative permittivity is characterized by the Drude model [42]

$$\varepsilon_{\rm m}(\omega)=\varepsilon_\infty-\frac{\omega_{\rm p}^2}{\omega(\omega+i\gamma)} \quad (1)$$

here $\varepsilon_\infty=3.7$ is the dielectric constant at infinite angular frequency, $\omega_{\rm p}$ stands for the bulk plasma frequency and is 9.1 eV, which represents the natural frequency of the oscillations of free conduction electrons, γ represents the damping frequency of the oscillations and is 0.018 eV, ω is the angular frequency of the incident wave in vacuum.

We use the transmission line theory [43] and an improved transmission model [44] to account for the dispersion properties of the structure. Based on the transmission line theory, the plasmonic graded grating waveguide is equivalent to a parallel connection of an infinite transmission line with the characteristic impedance of $Z_{\rm MIM}=\beta_0 w/\omega\varepsilon_0\varepsilon_{\rm air}$ (representing the MIM waveguide) and serial finite transmission line with the characteristic impedance $Z_{\rm s}$ terminated by a load $Z_{\rm L}$ (representing the stub). For simplicity, the stub section can be replaced by an effective impedance described by $Z_{\rm stub}=Z_{\rm s}(Z_{\rm L}-iZ_{\rm s}\ \tan(\beta_{\rm s}h))/(Z_{\rm s}-iZ_{\rm L}\ \tan(\beta_{\rm s}h))$, where $Z_{\rm s}=\beta_{\rm s}w/\omega\varepsilon_0\varepsilon_{\rm air}$ and $Z_{\rm L}=(\varepsilon_{\rm m}/\varepsilon_{\rm air})^{1/2}Z_{\rm s}$. $\beta_0(\beta_{\rm s})$ is the propagation constant of the fundamental propagating TM mode in the MIM waveguide (stub), h is the depth of the stub. Using the transmission line theory, the dispersion relation between the frequency and Bolch wave number $K=\alpha+i\beta$ of the entire system can be obtained as:

$$\cosh(Kp)=\cos(\beta_0 p)-i\sin(\beta_0 p)\left[\frac{Z_{\rm MIM1}}{2Z_{\rm stub1}}+\frac{Z_{\rm MIM2}}{2Z_{\rm stub2}}\right] \quad (2)$$

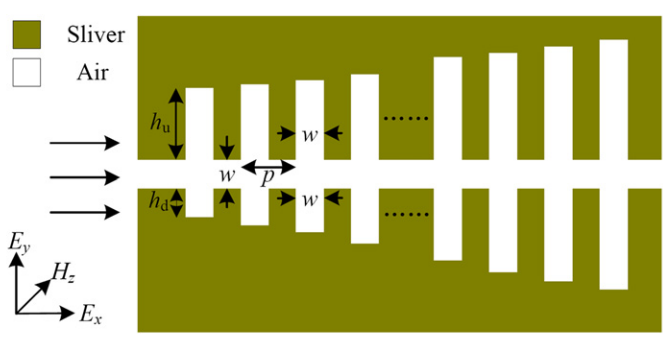

Fig. 1. Schematic diagram of the graded grating waveguide: $h_{\rm u}$ and $h_{\rm d}$ represent the upper and lower grating depth, respectively; p, the period of the grating; w, the width of the stubs and waveguide.

3. Numerical simulation results and analysis

Firstly, we study the dispersion properties of the graded grating waveguide. The dispersion relations of SPPs in the proposed structure for both loss and lossless metal cases are shown in Fig. 2(a). One can see that when the metal loss is considered, the band structure is unchanged except at the band edges. In Fig. 2(b), we show the evolution of propagation constant β at different frequencies with the lower grating depth, correspondingly, the upper grating depth changes linearly from 150 nm to 500 nm. It can find that the cut-off frequency has a red-shift with the increase of grating depth. So if the grade of the proposed structure is small enough, the dispersion relations are supposed to change gradually along the waveguide with the increasing grating depth. Then the group velocity $v_{\rm g}$ (defined as $\partial\omega/\partial\beta$), which is given by the slope of the tangent line of the dispersion, can be slowed down significantly when the incident frequency approaches to the cut-off frequency. In this way, the rainbow trapping of SPP waves could be achieved in the proposed configuration.

Successively, we study the group index $c/v_{\rm g}$ as a function of the frequency of incident wave at the given grating depth. The upper and lower grating depths are 295 nm and 195 nm, respectively, which correspond to a cut-off frequency of 140 THz. From Fig. 3(a), it can be seen that the group velocity can be significantly slowed down when the incident frequency approaches 140 THz. Fig. 3(b) shows the dependence of SPP intensity in the stubs on

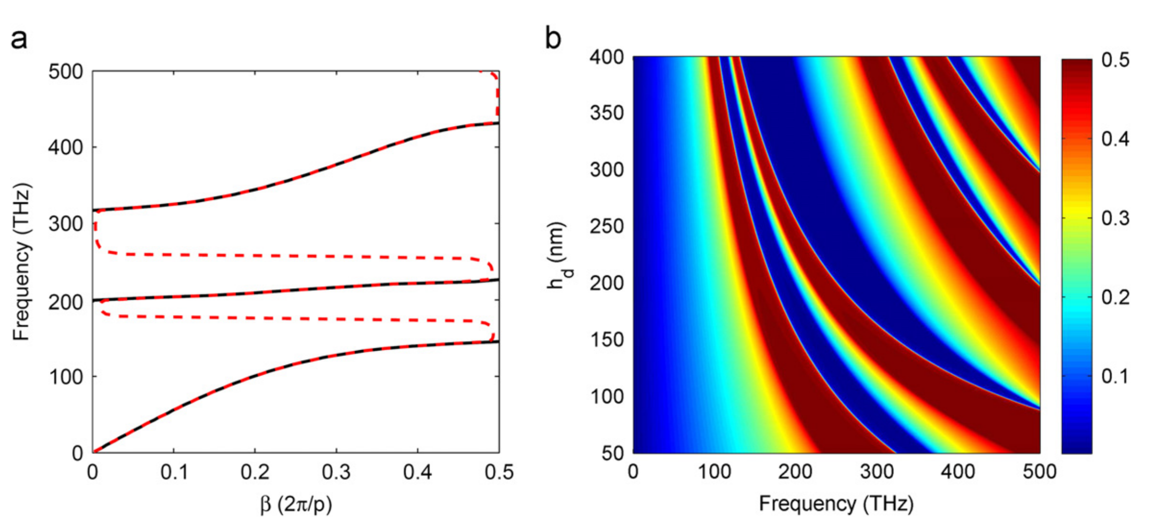

Fig. 2. (a) Dispersion curves calculated by transmission line theory for silver (red dashed line). The geometrical parameters of the proposed structure are $h_{\rm u}=295$ nm, $h_{\rm d}=195$ nm, $w=50$ nm, and $p=200$ nm. Also shown are the dispersion curves for lossless metal (black solid line). (b) Evolution of propagation constant β at different frequencies with the lower grating depth of $w=50$ nm and $p=200$ nm. Correspondingly, the upper grating depth changes linearly from 150 nm to 500 nm. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)