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A surface-plasmon-polariton wavelength splitter based on a metal–insulator–metal waveguide

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Abstract

A surface-plasmon-polariton (SPP) wavelength splitter based on a metal–insulator–metal waveguide with multiple teeth is proposed. Using the transfer-matrix method, a plasmonic band gap is identified in the multiple-toothed structure, and the splitting wavelength of the SPP splitter can be easily adapted by adjusting the widths of the teeth and the gaps. The proposed wavelength splitter is further verified through finite-difference time-domain (FDTD) simulations, in which SPPs with incident wavelengths of 756 nm and 892 nm are successfully split and guided in opposite directions in the waveguide, with extinction ratios of 30 dB and 29 dB, respectively.

Keywords: Wavelength splitter; Surface plasmon polaritons; Metal–insulator–metal waveguide; Transfer-matrix method; Finite-difference time-domain method

1. Introduction

Surface plasmon polaritons (SPPs) are the key to surpassing the diffraction limit of conventional optics and have recently been attracting increasing attention [1–4]. Many interesting experimental and theoretical studies of SPP-based subwavelength components have been reported in the past few years, such as metallic nanoparticles [5], nanohole arrays [6], metallic nanowires [7], grooves [8], and metal–insulator–metal (MIM) waveguides [9]. In the case of MIM waveguides, the SPPs are sustained in nanoscale effective areas, which opens up many possibilities for these devices in a broad range of applications, such as nanoplasmonic couplers [10,11], MIM splitters [12,13], and optical filters [14]. Bragg-type structures based on SPPs have been proposed in MIM waveguides; for example, the construction of metal-heterostructure-based Bragg reflectors and nanocavities on flat metallic surfaces by modulating the effective refraction index of metal-gap waveguides has been proposed [15,16], periodic changes in the dielectric materials of MIM waveguides have been utilized in the design of efficient subwavelength Bragg reflectors and microcavities [17], and the periodic structure formed by inserting insulators of alternating widths produces the functionality of a Bragg reflector [18,19]. In this paper, a wavelength splitter is proposed in which multiple-toothed structures are introduced into a MIM

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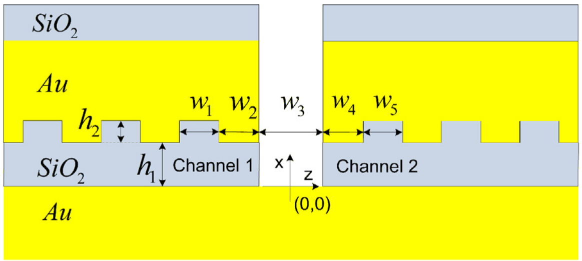

Fig. 1. A side-view schematic of the multiple-toothed MIM waveguide splitter in the *XOZ* plane. The origin of the axis is at the center of the narrow slit on the interface between the SiO_2 layer and the lower gold layer. w_1 and w_2 are the tooth and tooth-gap widths, respectively, in channel 1, and w_4 and w_5 are the corresponding parameters for channel 2.

waveguide on opposite sides of a narrow slit. Using the transfer-matrix method, a plasmonic band gap is identified in the multiple-toothed structure, which is associated with the geometrical structure parameters. The finite-difference time-domain (FDTD) method is employed to simulate the propagation of SPPs in the wavelength splitter. SPPs excited on the metal/insulator interface with wavelengths of 756 nm and 892 nm are split to opposite sides of the narrow slit; this result is well consistent with the analysis performed using the transfer-matrix method. Although only wavelengths of 756 nm and 892 nm are used to verify the properties of the wavelength splitter in our simulations, the design of the splitter can be easily modified for target wavelengths from the visible region to the near-infrared region by changing its geometrical parameters.

2. Theoretical analysis

A schematic diagram of the multiple-toothed MIM waveguide splitter is presented in Fig. 1: a metal–silica–metal structure with multiple teeth, split by a narrow slit, is immobilized on a glass substrate and covered with a SiO_2 film. A gold film, which is the type of metal film most often used for plasmonic applications, is used because of its relatively low loss in the visible and near-infrared ranges [20].

When a collimated polarized laser beam is incident on the structure from the top side, SPPs are excited at the gold/SiO_2 interface, propagate along the narrow slit, and then become coupled into opposite waveguide channels.

The dispersion equation for the MIM waveguide for TM_0 modes [21] is

$$(k_0^2\varepsilon_1-\beta^2)^{1/2}d=2\arctan\left[\frac{\varepsilon_1}{\varepsilon_2}\left(\frac{\beta^2-k_0^2\varepsilon_2}{k_0^2\varepsilon_1-\beta^2}\right)^{1/2}\right] \tag{1}$$

where $k_0=\omega/c$ is the free-space wave vector; ε_1 and d are the permittivity and thickness of the SiO_2 guiding layer, respectively; ε_2 is the real part of the permittivity of the gold film (the imaginary part of the gold permittivity is neglected in the theoretical analysis in the wavelength range of 650 nm to 1200 nm because it is sufficiently smaller than the absolute value of the real part) [22]; β is the propagation constant of the SPPs; and the effective refractive index is expressed as $N=\beta/k_0$.

The transfer-matrix method is applied to explain the propagation of SPPs in the multiple-toothed MIM waveguide. The continuity conditions [23] for H_y and $(1/n^2)(\partial H_y/\partial z)$ are imposed at the boundaries of one period, $z=(q-1)\Lambda$ and $z=q\Lambda$, in the multiple-toothed structure:

$$\begin{pmatrix}H_y(q\Lambda)\\H'_y(q\Lambda)\end{pmatrix}=M(w_2)M(w_1)\begin{pmatrix}H_y[(q-1)\Lambda]\\H'_y[(q-1)\Lambda]\end{pmatrix} \tag{2}$$

where

$$M(w_2)=\begin{pmatrix}\cos(\beta_2w_2) & \dfrac{N_2^2}{\beta_2}\sin(\beta_2w_2)\\ -\dfrac{\beta_2}{N_2^2}\sin(\beta_2w_2) & \cos(\beta_2w_2)\end{pmatrix} \tag{2a}$$

$$M(w_1)=\begin{pmatrix}\cos(\beta_1w_1) & \dfrac{N_1^2}{\beta_1}\sin(\beta_1w_1)\\ -\dfrac{\beta_1}{N_1^2}\sin(\beta_1w_1) & \cos(\beta_1w_1)\end{pmatrix} \tag{2b}$$

$$M(\Lambda)=M(w_2)M(w_1)=\begin{pmatrix}m_{11} & m_{12}\\ m_{21} & m_{22}\end{pmatrix} \tag{2c}$$

where Λ is the period of the structure and q is an integer. $H_y[(q-1)\Lambda]$ and $H_y(q\Lambda)$ are the magnetic-field values at $z=(q-1)\Lambda$ and $z=q\Lambda$, respectively, and the corresponding first derivatives of the magnetic field are $H'_y[(q-1)\Lambda]$ and $H'_y(q\Lambda)$, respectively. β_1 and β_2 are the propagation constants in each tooth and in each tooth gap, respectively, and the corresponding effective refractive indices are $N_1=\beta_1/k_0$ and $N_2=\beta_2/k_0$, respectively. $M(\Lambda)$ is the transfer matrix of one period.

The relation between the propagation constant β' of the multiple-toothed MIM waveguide and the transfer-matrix components of one period is expressed as follows: