



Analysis of the plasmonic power splitter and MUX/DEMUX suitable for photonic integrated circuits

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ABSTRACT

In this paper, the metal–insulator–metal (MIM) plasmonic directional coupler (PDC) with 45° waveguide bends based on surface plasmon polaritons (SPPs) excitation has been analyzed by the finite-difference time-domain (FDTD) numerical method. Effects of the variations of the coupler length and the metal gap thickness on the output powers and the propagation loss at 1550 nm wavelength have been studied. By choosing proper coupler lengths, power splitters with various output power ratios at 1550 nm wavelength and multi/demultiplexers, as some applications of the directional couplers have been proposed and their performances have been simulated.

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1. Introduction

Miniaturizing the size, increasing the speed and improving the performance of the optical devices have attracted many researchers' attentions in recent years. However, due to the optical diffraction limit, there is a basic limit for minimization of the size of the conventional optical devices [1,2]. For this purpose, photonic crystals (PCs) are the key components for photonic integrated circuits (PICs), in which the lightwave guidance through sharp bends with very low loss is possible. These structures are periodic structures and need at least five periods to acquire photonic band gap. Therefore, the dimensions of the PC devices are in the order of light wavelength [1].

Surface plasmon polaritons (SPPs) are perfect candidates to overcome the diffraction limit and to propagate lightwave in the nanoscale devices and PICs. Surface plasmons are electromagnetic excitations that propagate through metal–dielectric interfaces. The SPP energy is confined very well over the surface and decay exponentially in the normal directions of both media [2–6].

There are various geometries for plasmonic waveguides, the major of which are insulator–metal–insulator (IMI) and metal–insulator–metal (MIM) structures. Insulator–metal–insulator structures can propagate waves in a long distance but their spatial extent, the distance between the points in two cladding layers where the field decays to 1/e of its peak value, is larger than the wavelength. Also, their light confinement is poor due to the dielectric cladding layers. Metal–

insulator–metal configurations are appropriate choices for application in the optical devices. The lightwave is guided in the dielectric core of MIM structure with high confinement. Furthermore, their spatial extent is in the order of subwavelength. Due to the higher losses created by metal claddings, the propagation length of MIM waveguides is lower; but it is enough for nanophotonic applications [1,6,7].

Several SPP-based nanophotonic structures and devices, such as metallic strips and nanowires [8], Bragg reflectors [9–12], plasmonic waveguides [13,14], filters [15], Mach–Zehnder interferometers [1,16], sensors [17], switches [18,19], wavelength sorters and beam splitters [1,2,20–22] have been proposed and analyzed, in recent decade. Also, the SPP power splitters have been fabricated and their experimental results have been shown [23–26].

In this paper, performance of the MIM plasmonic power splitters with various output power ratios at the wavelength of 1550 nm and multi/demultiplexers based on directional couplers has been analyzed and simulated by the FDTD numerical method. In Section 2, the simulation method and in Section 3, the results of the analysis and simulation of the plasmonic directional couplers (PDCs). Power splitters and multi/demultiplexers are described and discussed. The article is concluded in Section 4.

2. Analysis and simulation method

The finite-difference time-domain (FDTD) numerical method based on Yee algorithm, as a general and powerful algorithm for calculating the electromagnetic field distributions in structures with arbitrary geometry, has been employed for simulation of our proposed structures [27,28]. Since the simulation area is dispersive, the convolutional perfectly matched layer (CPML) has been used as the

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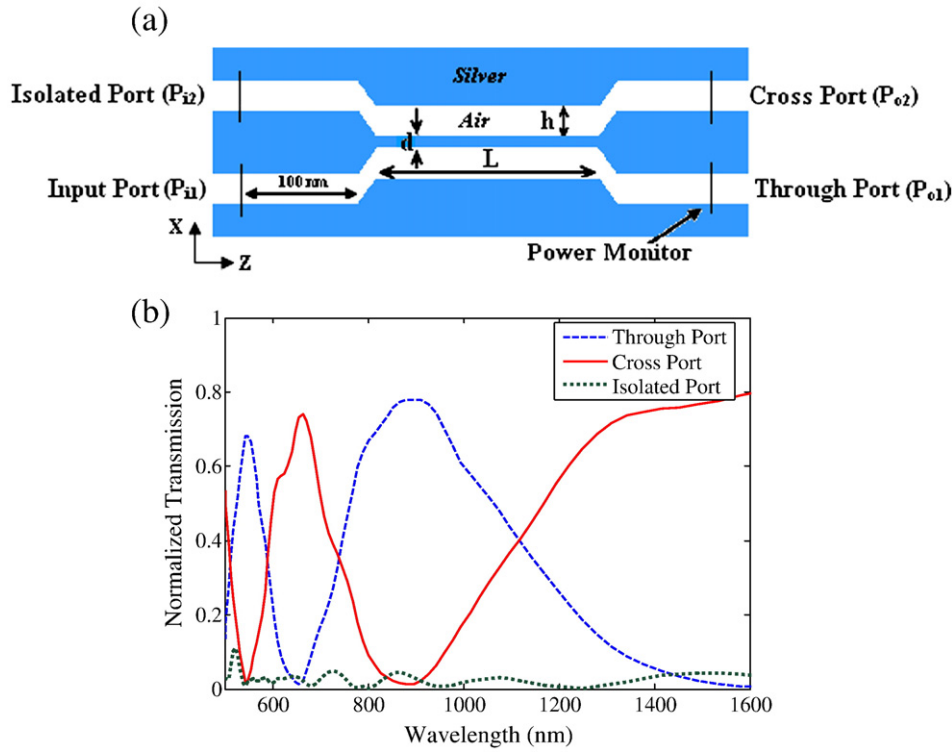


Fig. 1. The schematic view (a) and the normalized transmission spectra (b) of the plasmonic directional coupler with 45° bends.

absorbing boundary conditions [28]. The number of CPML layers is 11. The step size of the FDTD cell in x and z directions are $\Delta x = \Delta z = 1$ nm and the time step is chosen by Courant condition to be $\Delta t = 0.95 / \left(c \sqrt{(\Delta x)^{-2} + (\Delta z)^{-2}} \right)$, where c is the free space speed of light. We have utilized MATLAB and C++ programming languages for our analyses and simulations. The time steps in our simulations are 60,000 and the dimensions of the simulation region are $400 \text{ nm} \times 3000 \text{ nm}$.

Since SPPs are excited by only TM polarization, a TM polarized pulse with electromagnetic field components of H_y , E_x and E_z is launched to the MIM device, such as Fig. 1 [4,13].

The dispersion relation of SPP modes in two adjacent metal gap waveguides, with the guide width, h and metal gap thickness, d , has been obtained from the following equation [29,30]:

$$\frac{1-b}{1+b} = \pm e^{pd}, \quad (1)$$

with

$$b = \frac{[\varepsilon_m k + \varepsilon_d p - (\varepsilon_m k - \varepsilon_d p)e^{-2kh}] \varepsilon_m k}{[\varepsilon_m k + \varepsilon_d p + (\varepsilon_m k - \varepsilon_d p)e^{-2kh}] \varepsilon_d p}, \quad (2)$$

where $k = \sqrt{\beta^2 - k_0^2 \varepsilon_d}$ and $p = \sqrt{\beta^2 - k_0^2 \varepsilon_m}$ are the transverse propagation constants of the SPPs in dielectric and metal layers with relative permittivities of ε_d and ε_m , respectively. $k_0 = 2\pi/\lambda$ is the free space wave number of the lightwave, where λ is the free space wavelength. The positive and negative signs in Eq. (1) are related to the symmetric and antisymmetric SPP modes in the waveguide, respectively. The propagation constant of SPPs can be defined as $\beta = (\beta_s + \beta_a)/2$ [29,30], where β_s and β_a are the symmetric and antisymmetric propagation constants.

The coupling region has a major effect on the switching performance of the directional coupler. The coupling length, L_c , is the distance over which the energy of SPP modes couples completely

from one waveguide to the adjacent one, which depends on the difference between the propagation constants, β_s and β_a [2,30]:

$$L_c = \frac{\pi}{\beta_s - \beta_a} \left(m + \frac{1}{2} \right), \quad m = 0, 1, 2, \dots \quad (3)$$

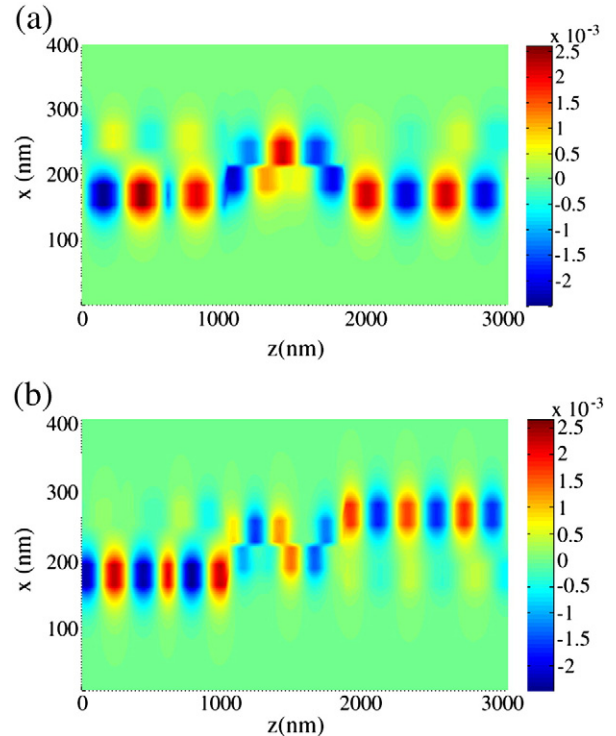


Fig. 2. Distributions of the magnetic field, H_y , of the directional coupler of Fig. 1 with $h = 30$ nm, $d = 10$ nm and $L = 800$ nm at incident light wavelengths of (a) $\lambda = 881$ nm and (b) $\lambda = 655.4$ nm.

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