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Photonics and Nanostructures – Fundamentals and Applications 9 (2011) 308–314
www.elsevier.com/locate/photonics
PHOTONICS AND NANOSTRUCTURES
Fundamentals and Applications

The plasmonic folded directional coupler

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Received 25 January 2011; received in revised form 21 March 2011; accepted 21 March 2011
Available online 29 March 2011

Abstract: We study the properties of a novel type of plasmonic coupler, the folded directional coupler, composed of two MIM waveguides in silver. We calculate the transmission properties of three designs, and show that coupling lengths as small as $\lambda/5$ can be achieved at 1.55 μm. We show that the theory of the photonic crystal folded directional coupler can straightforwardly be modified to give a simple and quite accurate model for the plasmonic folded directional coupler, and that metallic absorption reduces the contrast between maximum and minimum transmittance significantly below that in the lossless case.

Keywords: Photonic crystals; Directional couplers; Plasmonic couplers

1. Introduction

Directional couplers are important devices in photonics, with many applications [1–5]. They have been implemented for example in photonic crystals [6–8] where they found applications such as power splitters and combiners, wavelength selective filters, wavelength division multi/demultiplexers and switches [9–14]. Typical coupling lengths in this four-port device in photonic crystals are in the range four lattice constants to twenty lattice constants [11,15], when used at wavelengths near 1.55 μm. In plasmonic circuits, they have also been studied [16–19], with typical coupling lengths being in the range from 0.5λ to 2λ at the wavelength of 1.55 μm, when the metal gap thickness in the coupler varies from 10 nm to 30 nm. By contrast, the folded directional coupler is a two-port device, which has so far only been studied in photonic crystals (PCFDC) [20–22]. It has been shown that it can provide an ultra-compact, high quality factor (Q) notch-rejection filter, with a two-dimensional device less than 3 μm in length being capable of giving a Q factor of 22,000 [20]. It functions in a way which can be modelled by summing a geometric series associated with the field bouncing off the ends of the coupler. This summation results in fine oscillations in the response that can be traced back to the same source as the oscillations in Fabry–Perot fringes – namely the field bouncing between the partially reflective mirrors.

In this paper, we consider for the first time in the literature the operation of the plasmonic folded directional coupler (PFDC). Our aim is not to optimise the structure for a particular application, but to establish that it does have promise in applications requiring sub-wavelength scale plasmonic couplers, and that it can be modelled quite accurately by a simple formula, adapted to the plasmonic case from the corresponding photonic crystal geometry. We show that the PFDC can provide ultra-compact designs, with the device length separation of successive maxima and minima in transmittance being as small as 0.2 μm at the wavelength of 1.55 μm. Its maximum and minimum transmittance values differ by around 60%, rather than the range of near 100% possible in the PCFDC, and of course the Q value

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doi:10.1016/j.photonics.2011.03.005

possible in the plasmonic device is much lower due to Ohmic losses than that of the photonic crystal device.

We begin with a brief description of the physical principles and characteristics of the PCFDC. We then present the results of finite difference time domain (FDTD) studies of the transmission properties of PFDCs, concentrating on a design for 1.55 μm having air waveguides separated by silver. We discuss the similarities and differences which emerge from the results of the numerical simulations, correlating them with the properties of the waveguide modes in the regions of the PCFDC. We show how a simple model of the PCFDC can be adapted to the PFDC, and that it gives results of quite good accuracy, before making concluding remarks.

2. The photonic crystal folded directional coupler

The geometry of the PCFDC is shown in Fig. 1(left panel). An input waveguide in the PC enters from the top (region $M1$), and overlaps with an output waveguide which leaves at the bottom (region $M3$). The two waveguides overlap for a length L, which defines region $M2$.

The semi-analytic model of the PCFDC developed in [20] by White et al. uses the tight-binding approximation, and relies only on the fields in the overlap region $M2$. These are taken to be dominated by single symmetric $|\psi_+\rangle$ and antisymmetric $|\psi_-\rangle$ states, with respective propagation constants along the direction of the waveguides of β_+ and β_-. The following assumptions are made:

(1) the fields in the input and output waveguides are well represented as linear combinations of the symmetric and antisymmetric states

$$|\psi_L> = \frac{(|\psi_+\rangle + |\psi_-\rangle)}{\sqrt{2}}, \quad |\psi_R> = \frac{(|\psi_+\rangle - |\psi_-\rangle)}{\sqrt{2}}; \tag{1}$$

(2) the propagation constants of the modes in the left and right waveguides are to a good approximation $\bar{\beta} = (\beta_+ + \beta_-)/2$;

(3) when modes approach the ends of region $M2$, they are re-expressed as modes in single waveguides, with the mode approaching the closed end being reflected without change of amplitude or phase, and with the mode approaching the open end being transmitted without reflection.

The result of these assumptions is that the reflected field can be expressed in geometric series form, and evaluated to give the reflectance (R) and transmittance ($T = 1 - R$) [20]:

$$R = |\rho|^2 = \frac{\cos^4(L\Delta\beta)}{\cos^4(L\Delta\beta) + 4\sin^2(L\Delta\beta)\cos^2(L\bar{\beta})}, \tag{2}$$

where $\Delta\beta = |\ \beta_+ - \beta_-\ |/2$. One significant feature of Eq. (2), coming from the Fabry–Perot aspects of the PCFDC model, is the location of reflectance maxima:

$$R = 1: \quad L = \frac{(m + 1/2)\pi}{\bar{\beta}}, \quad m = 0, 1, 2, \ldots. \tag{3}$$

The half-width of the reflectance resonance is given by

$$\Delta\omega_{1/2} = \frac{\cos^2(L\Delta\beta)}{(2L\bar{\beta}_1)}, \tag{4}$$

where $\bar{\beta}_1$ is the ω derivative of $\bar{\beta}$ at the resonance frequency. The half-width is controlled by the parameter $\Delta\beta$, and so reflects the directional coupler aspect of the PCFDC model.

We show below how to adapt this model so that it becomes a useful predictor of the behaviour of the PFDC.

3. The plasmonic folded directional coupler

We employed the finite-difference time-domain (FDTD) numerical method [23] to simulate three PFDC structures with air waveguides embedded in silver. The

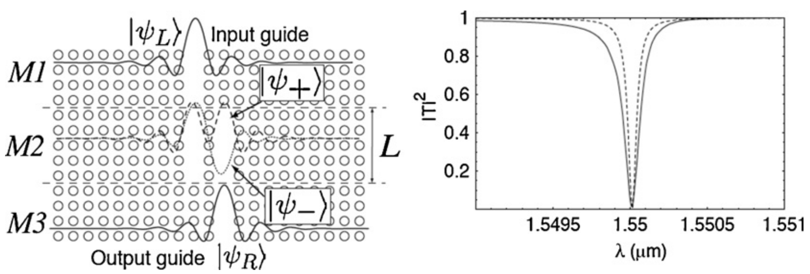

Fig. 1. (Left) The geometry of the FDC in a photonic crystal. (Right) Transmission spectrum of the FDC in this figure near the resonance at λ = 1.55 μm. Solid curve: full numerical calculation. Dashed curve: approximate result obtained from Eq. (2). From Ref. [20].