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Analysis of coupling in the semi-cylindrical surface plasmonic couplers

Pouya Dastmalchi, Nosrat Granpayeh*, Majid Rasouli Disfani

Faculty of Electrical and Computer Engineering, K. N. Toosi University of Technology, Tehran, Iran

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ABSTRACT

In this paper, we have investigated the performance of a nano-optical directional coupler based on gap plasmon waveguides. The coupler consists of two waveguides having a localized coupled plasmon propagating between two semi-cylindrical surfaces. It is clear that the wave number and correspondingly light confinement in the waveguides are the most effective parameters in coupling strength and coupling length. Some expected and unexpected dependencies of the coupling length on the structure parameters are shown. Simulation results of the coupler obtained by the compact-2D finite-difference time-domain (FDTD) method comply with those derived by an analytic method with the aid of the finite-element frequency-domain (FEFD) software package of COMSOL. The considered structures, because of their small coupling length and dimensions are appropriate for use in optical integrated circuits.

1. Introduction

Achieving high speed and high efficiency information processing is one of the major goals in modern technology. Thus light could be an efficient carrier in optical integrated circuits and devices. In conventional dielectric optical devices, the diffraction of light is the limit of miniaturizing the devices [1]. This means that, these structures could not confine and localize the electromagnetic waves within a region smaller than their wavelength. To overcome this problem these materials have been replaced by metals, and surface plasmons have been used in metallic nanostructures [2–4]. In recent years, different metallic nanostructures, such as metallic gaps [5–7], triangular metal wedges [8,9], metal V-grooves [10,11] and SPP band gap structure [12,13] have been widely studied and there have been great interests in the novel applications of these structures at optical frequencies. One of the most important devices in optical communications is directional coupler, the plasmonic types of which can be used in integrated structures [14,15]. Similar optical couplers have been designed by other materials such as photonic crystals [16] but the plasmonic ones could achieve considerably smaller dimensions and better confinement.

Coupling can be investigated from two points of view. From one side, it can be related to the crosstalk and demonstrates how much the plasmonic components can be integrated. On the other side, verifying the coupling between waveguides and investigating the effects of the parameters of the structures on coupling strength can lead to the design of directional couplers to be used in integrated optical circuits.

In this paper, after introducing a fundamental mode of the plasmonic waveguide which is used in our structure, we have demonstrated the effects of important parameters of a novel directional gap plasmon coupler on its coupling length. There are some numerical methods, such as finite-difference time-domain (FDTD) and finite-element method (FEM) that can be used for simulation of these structures to obtain their characteristics. The structures have been simulated by compact FDTD method and the results have been confirmed by using an analytic method with the aid of the commercial finite-element frequency-domain (FEFD) software package of COMSOL. Finally, a method for reduction of the coupling length of the plasmonic coupler has been proposed.

2. Coupler structure and analysis methods

We have investigated a coupler consisting of two slot waveguides, having a localized coupled plasmon propagating between two semi-cylindrical surfaces of radii R. The slot widths are W and the separation distance between them is S (Fig. 1). The permittivities of the metal and cladding are ε_m, ε_c, respectively.

For the fundamental mode at the free space wavelength of 632.8 nm, which we are focused on, the symmetric features of electric and magnetic field distributions of the anti-symmetric coupled semi-cylindrical surface plasmons (ACSCSPs) in each of these identical waveguides, shown in Fig. 2, are similar to those in anti-symmetric coupled wedge plasmons (ACWPs) [17]. The origin of the typical distributions of the electric field of this mode is that the charges are distributed anti-symmetrically across the gap and

* Corresponding author at: K. N. Toosi University of Technology, Seyedkhandan, Dr. Shariati Ave, P. O. Box: 16315-1355, Tehran, Iran. Tel.: +98 21 8846 9465; fax: +98 21 8846 2066.
E-mail address: granpayeh@eetd.kntu.ac.ir (N. Granpayeh).

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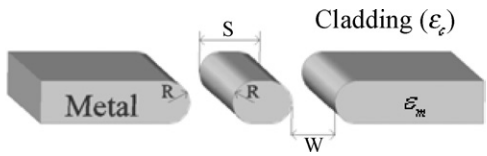

Fig. 1. Configuration of the plasmonic coupler under study consisting of two identical slot waveguides of width *W* separated by a metal strip of width *S*. The radii of the semi-cylindrical surfaces are *R*.

Table 1
Propagation lengths of semi-cylindrical waveguides.

Radius of the surfaces (R) (nm)	Slot width (W)(nm)	Propagation length (L_p) (μm)
30	50	5.3
30	100	7.6
50	50	6.7
50	100	10.5

symmetrically with respect to *x*-axis on each semi-cylindrical surface (Fig. 3(b) and (c)). The symmetric features of the magnetic field components can be obtained by the symmetry of the electric field components, Maxwell equations and the direction of propagation.

In comparison to the rectangular gap plasmon waveguides which have been considered in the previous works, the waveguide with semi-cylindrical surfaces has lower loss. One of the reasons can be the absence of the sharp tips. In plasmonic waveguides the sharp tips play main role in raising the loss [17].

The propagation length, L_p, is defined as the distance which a mode propagates before decaying to e^{-1} of its original power, so it can illustrate the amount of loss in plasmonic waveguides. As much as loss increases the propagation length decreases and vice versa. The propagation length of the plasmonic waveguides can be calculated by the imaginary part of the propagation constants [3]:

$$L_p = \frac{1}{2Im(\beta)} \quad (1)$$

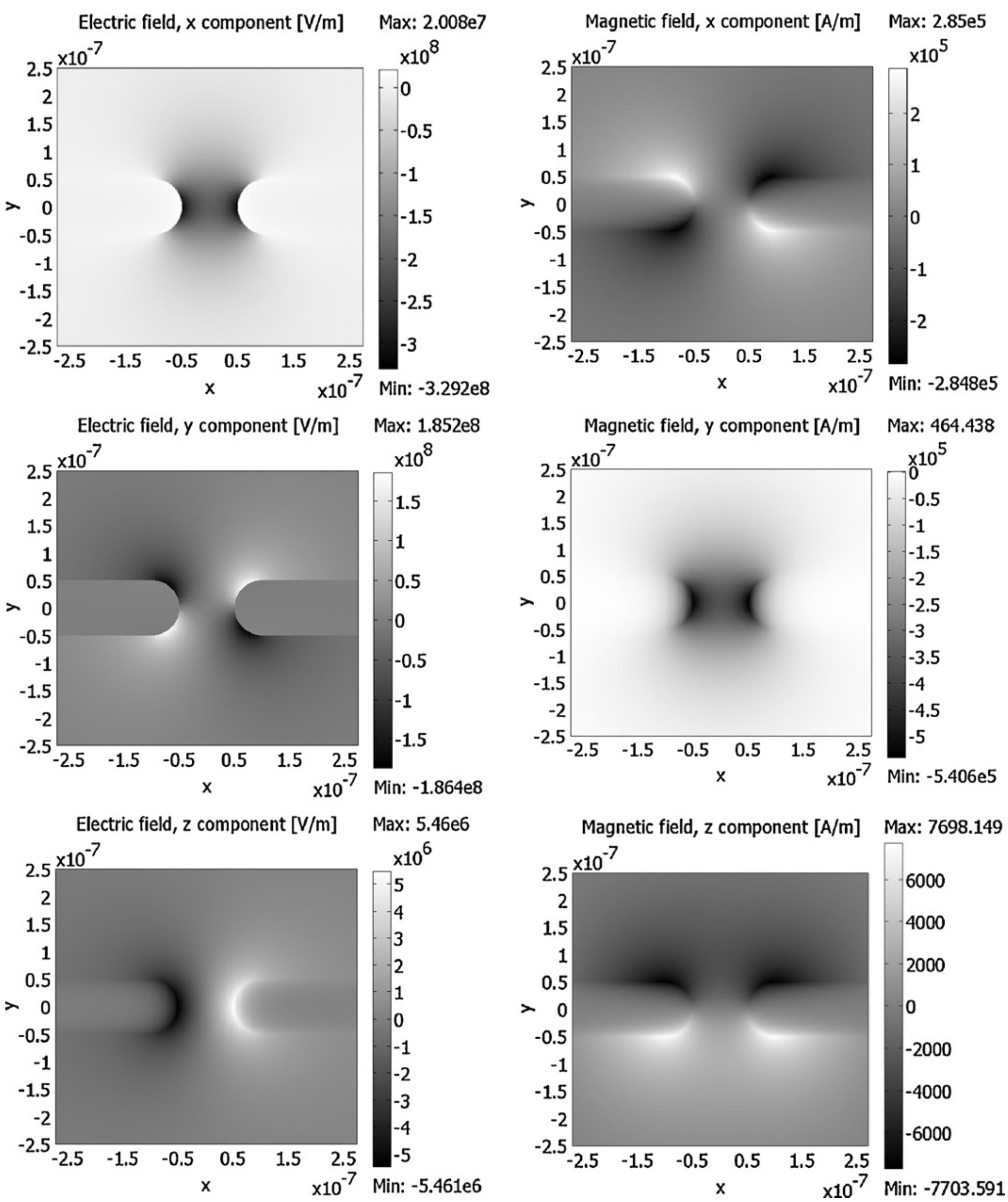

Fig. 2. Distributions of the components of the electric and magnetic fields between two semi-cylindrical surfaces of the silver in vacuum. The structure parameters are: $R = 50$ nm, $W = 100$ nm, $\lambda = 632.8$ nm and $\varepsilon_m = -16.2 + 0.52i$.