



Low-loss, compact waveguiding with TE mode in metal/dielectric waveguides for planar lightwave circuit

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ABSTRACT

We propose a low-loss metal/dielectric waveguide for compact planar lightwave circuit. The basic waveguide structure is a metal-defined high-index-contrast strip waveguide based on silicon/silica. As the guide is designed for TE single mode waveguiding, extremely low propagation loss (e.g. <0.04 dB/cm), very low bend loss (e.g. 0.0043 dB/90°-turn) and small waveguide pitch of zero-cross-talk are theoretically achievable, and can be further improved by compromising with component size and density. Examples of multi-bends and device integration are demonstrated with numerical simulations. The proposal is compatible with silicon technology and appealing for development of silicon-based planar lightwave circuit.

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1. Introduction

In developing ultra-compact integrated planar lightwave circuits, various novel waveguide structures were proposed in recent years, including dielectric-based photonic crystal (PC) waveguides [1], metal/dielectric-based plasmonic waveguides [2–14], and dielectric-based slot waveguides [15,16]. The main goal of these waveguides is to realize sharp bending and small pitch required for high integration, while still being able to form functional devices. Meanwhile, silicon strip waveguides based on high-index-contrast demonstrated strong potential for compact integration [17–19] (experimental losses of 0.086, 0.013, and 0 dB was reported in Ref. [17] for a 90° bend with radius of 1, 2 and 5 μ m respectively at the wavelength of 1500 nm), besides silicon is of one's particular interest for integrated electronics and photonics. In spite of fabrication challenges, the PC waveguides and slot waveguides in principle do not show advantage over the silicon strip waveguides for chip-on high integration in aspects of both sharp bending and small waveguide pitch. But for silicon strip waveguide, as single mode waveguiding is usually needed, its core width has to be very narrow (e.g. <300 nm) because of the high in-

dex of silicon (~ 3.5); as a result, the field confinement in the core region is weak and the waveguide pitch has to be dramatically increased to achieve minimum cross-talk [18]. The plasmonic waveguides are able to strongly confine the field for sharp bending and have excellent isolation of waveguides for extremely small pitch, but very high propagation loss (typical propagation length ranges from several to tens of micrometers) prohibits long-range transmission of waves [2–12], e.g. on a scale of millimeters. There are also long-range surface plasmon (LRSP) waveguides based on planar metal film stripes embedded in dielectrics, but the in-plane bend radius has to be very large (on a scale of centimeters) to keep a low bending loss [13,14], e.g. ~ 1.5 dB loss for 1 cm radius and <0.1 dB for 2 cm radius theoretically [13].

In additional review, a metal–dielectric–metal (MDM) waveguide with very narrow dielectric region supports the fundamental transverse-magnetic mode (TM₀) of surface plasmon (SP) waves with no cut-off width [20,21], as schematically shown in Fig. 1a. Due to high intensity of field at the metal–dielectric interfaces and that penetrating into the metal, strong propagation loss is induced. For the fundamental transverse-electric mode (TE₀) in the MDM waveguide, it exists only if the dielectric width is beyond a cut-off. The maximum field intensity is located in the middle of the waveguide, as schematically shown in Fig. 1b, thus the field penetrating into the metal is relatively much weaker compared to

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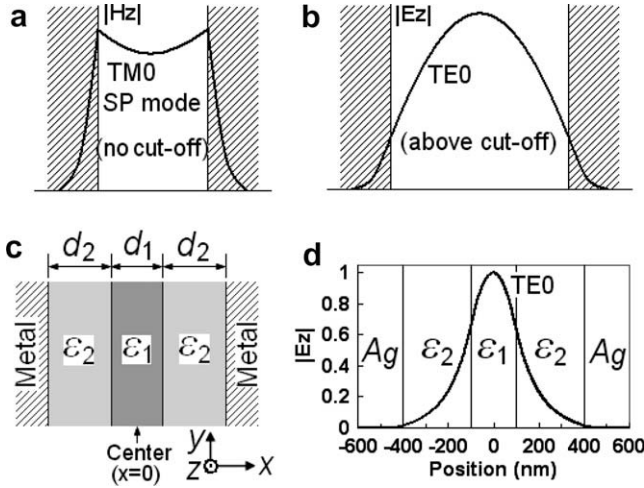


Fig. 1. (a) Schematic distribution of transverse field (H_z) of the plasmonic TM0 SP mode in a MDM waveguide. (b) Schematic distribution of transverse field (E_z) of the TE0 mode in a MDM waveguide. (c) Schematic illustration of the proposed MdDdM waveguide. $\epsilon_1 > \epsilon_2$. (d) Transverse field distribution (E_z) of the TE0 mode in the MdDdM waveguide, analytically calculated with $d_1 = 200$ nm, $d_2 = 300$ nm, $\epsilon_1 = 12.25$, $\epsilon_2 = 2.25$, and $\epsilon_3 = -82 + 8.3i$ for metal of silver at the vacuum wavelength of 1500 nm.

that of the TM0 SP mode, and the propagation loss is also much smaller [20,21]. But for single mode long-range waveguiding, with the dielectric width just beyond the cut-off, the power loss due to field penetration into the metal is still considerable.

In this letter, we propose to achieve sharp bending, zero-cross-talk and extremely low-loss waveguiding with TE0 mode in metal-defined high-index-contrast waveguides, so called “MdDdM waveguide” [“MdDdM” stands for “Metal–dielectric (low-index)–Dielectric (high-index)–dielectric (low-index)–Metal”, which is schematically illustrated in Fig. 1c. The MdDdM waveguide takes advantages of silicon strip waveguide and MDM waveguide, meanwhile suppresses their disadvantages for single mode waveguiding. Demonstration of its performance in this work is based on two-dimensional analyses. Fig. 1d shows field distribution of the TE0 mode in a MdDdM waveguide, which is analytically calculated for high-index-dielectric width $d_1 = 200$ nm, low-index-dielectric width $d_2 = 300$ nm, high-index-dielectric permittivity $\epsilon_1 = 12.25$ (silicon), low-index-dielectric permittivity $\epsilon_2 = 2.25$ (silica), and metal permittivity $\epsilon_3 = -82 + 8.3i$ (silver) at the vacuum wavelength of $\lambda_0 = 1500$ nm. It is shown that the field is highly confined within and around the high-index-dielectric core region, as such the field penetrating into the metal becomes very weak, which results in reduced propagation loss. As we increase the low-index dielectric width (d_2), the propagation loss can be further reduced to an extremely low level.

2. Characteristics of low-loss waveguiding and bending

In Fig. 1d, the transverse electric-field E_z of TE0 mode in the MdDdM waveguide can be generally written as:

$$E_z(x) = \begin{cases} A_0 e^{-\gamma_3(x-d_1/2-d_2)} & (x > d_1/2 + d_2) \\ B_0 e^{\gamma_2(x-d_1/2-d_2)} + C_0 e^{-\gamma_2(x-d_1/2)} & (d_1/2 < x < d_1/2 + d_2) \\ D_0 e^{\gamma_1(x-d_1/2)} + E_0 e^{-\gamma_1(x+d_1/2)} & (-d_1/2 < x < d_1/2) \\ F_0 e^{\gamma_2(x+d_1/2)} + G_0 e^{-\gamma_2(x+d_1/2+d_2)} & (-d_1/2 - d_2 < x < -d_1/2) \\ H_0 e^{\gamma_3(x+d_1/2+d_2)} & (x < -d_1/2 - d_2) \end{cases} \quad (1)$$

in which $\gamma_i = \sqrt{\beta^2 - k_0^2 \epsilon_i}$, $i = 1$ (high-index-dielectric), 2 (low-index dielectric) and 3 (metal), are transverse propagation constants (along the x -axis) in the media, β is the propagation constant along the waveguide (along the y -axis), and $k_0 = 2\pi/\lambda_0$ is the vacuum wave vector. $A_0, B_0, C_0, D_0, E_0, F_0$, and H_0 are constants of mode amplitudes at the interfaces ($x = \pm d_1/2, \pm(d_1/2 + d_2)$). Applying the boundary conditions that E_z and $\partial E_z / \partial x$ must be continuous at the interfaces, we derived the dispersion relation of the TE0 mode in the MdDdM waveguide as follows:

$$e^{\gamma_1 d_1} = \frac{(\gamma_2 - \gamma_3)(\gamma_1 + \gamma_2) + (\gamma_2 + \gamma_3)(\gamma_1 - \gamma_2)e^{2\gamma_2 d_2}}{(\gamma_2 - \gamma_3)(\gamma_1 - \gamma_2) + (\gamma_2 + \gamma_3)(\gamma_1 + \gamma_2)e^{2\gamma_2 d_2}}, \quad (2)$$

Solving Eq. (2), the waveguide propagation constants β and γ_i ’s can be obtained.

In Fig. 2, we plotted curves showing the dependence of real and imaginary parts of propagation constants (β) of TE0 mode in the MdDdM waveguide on the width of low-index dielectric (d_2). The imaginary part can be used to determine the propagation length (L_p) with the relation $L_p = \lambda_0 / [4\pi \cdot \text{Im}(\beta/k_0)]$, which is also indicated in Fig. 2b. Thus, to achieve lower propagation loss with even wider low-index dielectric, the wave is still in the TE0 mode form and the real propagation constant maintains at a saturated constant value [shown in Fig. 2a]. It can be derived that the MdDdM waveguide circuits can be theoretically designed such that the propagation loss is reduced to a required low level by adjusting the width of low-index dielectric, and the waveguide pitch is reduced down enough if only the width of metal between neighboring waveguides is larger than its penetration depth (e.g. tens of nanometers).

The MdDdM waveguide was also shown to support sharp bending with very low loss. In Fig. 3, we studied transmission of light ($\lambda_0 = 1500$ nm in all this study) through a 90° bend with different radii with the finite-difference time-domain (FDTD) simulations [22]. Fig. 3a is a schematic illustration of the structure in the analysis. Fig. 3b shows dependence of the bend loss on the radius as light transmit through the 90°-bend of the MdDdM waveguide and those without the metal clad (i.e. the outmost medium is air, “o” marked) in comparison. Here discrete points were calculated and smoothly linked into the curves as shown. It is observed that, with the metal clad, the bend loss is greatly reduced, particularly for small bend ra-

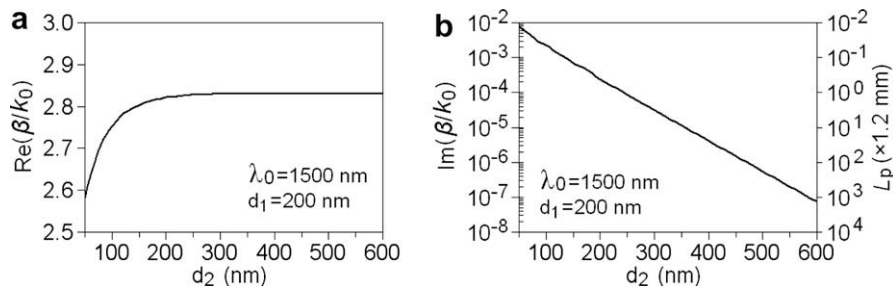


Fig. 2. (a) Real and imaginary parts of the propagation constants (normalized with k_0) of TE0 mode as functions of the width of the low-index dielectric (d_2) of the MdDdM waveguide. Labels of the secondary vertical axis of (b) indicate corresponding wave propagation length (L_p).

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