Ultracompact Plasmonic-Mode-Assisted Polarization Splitter with A Large Fabrication Tolerance

Yin-Jung Chang, Wei-Lun Li, and Hong Chen
Department of Optics and Photonics
National Central University
Jhongli, 32001, Taiwan (R.O.C.)
yjchang@ncu.edu.tw

***Abstract*— An ultra-compact plasmonic-mode-assisted polarization splitter based on directional coupler is proposed and investigated analytically and numerically. A large modal birefringence of > 0.69 is estimated, enabling a clean polarization separation within 5.6 μm.**

Keywords-Polarization splitters; surface plasmons; plasmonic waveguides

I. Introduction

The advances in nanotechnologies have made the implementation of photonic integrated circuits (ICs) at deep submicron/nanoscale possible in recent years. Featuring strong field confinement in dimensions smaller than the diffraction limit, plasmonic waveguide devices have presented what might be the most promising solution in realizing optical nanocircuitry.

Despite their inherent sub-wavelength guidance capability, plasmonic waveguides suffer from high propagation loss due mainly to the energy dissipation in the conductor (ohmic loss) [1]. This limits their propagation length from a few to hundreds of microns at best, depending on the operating wavelength ($\sim 30\ \mu$m in visible and $\sim 300\ \mu$m in near infrared). On the other hand, nowdays the silicon (Si) core of a single-mode waveguide operating in optical telecommunication bands can be only a few hundred nanometers. For example, the state-of-the-art strip waveguide with a cross-sectional area of $200 \times 400\ \mathrm{nm}^2$ [2] has been experimentally demonstrated. In view of bringing light from long-haul optical networks into nanoscale photonic ICs, combining the advantages from both dielectric- and plasmonic-based structures, which may be complimentary to each other in nature, could pave the way toward high-performance, ultrahigh-density optical nanocircuitry in the future.

Symmetric metal/multi-insulator/metal and asymmetric metal/multi-insulator (MMI) structures have been explored in the design of low loss, ultracompact plasmonic Bragg gratings [3, 4] and 90° waveguide bends for optical nanocircuitry [5]. In this paper, a new polarization splitter (PS) based on an asymmetric metal/multi-insulator directional coupler (DC) is proposed and investigated. Advantages and performance of this novel PS as well as its fabrication tolerance are revealed and briefly discussed.

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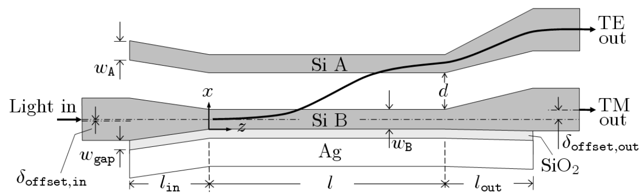


Figure 1. Two-dimensional (2-D) schematic of the proposed polarization splitter in asymmetric metal/multi-insulator configuration.

II. Design Principles

The proposed PS is depicted schematically in Fig. 1. It is a DC-based design with one arm (guide B) being in asymmetric silicon/silica/silver configuration and the other a simple Si waveguide (guide A). The respective refractive indices of Si, silica, and silver are $n_{\mathrm{Si}} = 3.5$, $n_{\mathrm{silica}} = 1.46$, and $n_{\mathrm{Ag}} = 0.1441 - j11.2141$ at a free-space wavelength $\lambda_0 = 1550$ nm. The background material is assumed to be air. The silica gap width w_{gap} is set to 100 nm. The guided mode supported by the composite guide B is excited by a 450-nm-wide Si waveguide followed by a linear taper of length l_{in}. The Si core width along the straight section of guide B is 200 nm, whereas the silver region is 300-nm-wide throughout the device. Due to limited computational resources, a 2-D electromagnetic problem was assumed in both analytical calculations and numerical simulations.

The modal birefringence associated with the asymmetric MMI configuration is critical to the PS design as it presents what might be the only enabling mechanism for the polarization splitting in DC-based configuration. In the structure presented above, it is shown that the effective index of the TM mode ($N_{\mathrm{eff,TM}}$) is a strong function of the silica gap width. The largest modal birefringence occurs when the silver region is completely removed but is inevitably accompanied by a minimum TM field confinement. Since $N_{\mathrm{eff,TE}}$ is larger than $N_{\mathrm{eff,TM}}$ by a large margin of more than 0.696 for $w_{\mathrm{gap}} \geq 100$ nm and beyond, the coupling length of the TE polarization is significantly shorter than that of the TM. Consequently, the cross path is intended for the TE propagation while the through path is for the TM. The performance of the present PS may be strictly described in terms of the splitting ratio (SR) and extinction ratio (ER) defined as follows:

$$\mathrm{SR_{TE}} = 10 \times \log\left(T_{\mathrm{A,TE}}/T_{\mathrm{B,TE}}\right), \quad (1)$$

$$\mathrm{SR_{TM}} = 10 \times \log\left(T_{\mathrm{B,TM}}/T_{\mathrm{A,TM}}\right), \quad (2)$$

$$\mathrm{ER_{cross}} = 1 \times \log\left(T_{\mathrm{A,TE}}/T_{\mathrm{A,TM}}\right), \quad (3)$$

$$\mathrm{ER_{thru}} = 10 \times \log\left(T_{\mathrm{B,TM}}/T_{\mathrm{B,TE}}\right), \quad (4)$$

where $T_{\mathrm{A},i}$ ($T_{\mathrm{B},i}$), $i = \{\mathrm{TE, TM}\}$, represents the normalized power transmission at the end of guide A (guide B) associated with the TE or TM mode.

III. Results and Discussions

The coupling length and $\mathrm{SR_{TE}}$ of the TE mode with varying separation distance d were first studied using modified coupled-mode equations applicable to a lossy waveguide system [6]. The initial design was then optimized by minimizing the $T_{\mathrm{B,TE}} \times T_{\mathrm{A,TM}}$ product that is a function of d and l through finite-element-based numerical simulations (Fig. 2). This ensures the maximum simultaneous cancellation of the modal power at the undesired output port. The optimized structure parameters are given in [6].

The time-average power flow associated with the respective TE and TM modes in the optimized PS is shown in Fig. 3. The figures of merit defined in (1) – (4) of the device are given in Table I. On the other hand, assume the device length is unchanged, the fabrication tolerance studies reveal that, at a 10-dB criterion for all figures of merit, the proposed PS has a relatively large fabrication tolerance of ± 60 nm ($\pm 30\%$) for the Si core width, which translates to ± 30 nm ($\pm 30\%$) for the silica gap region.

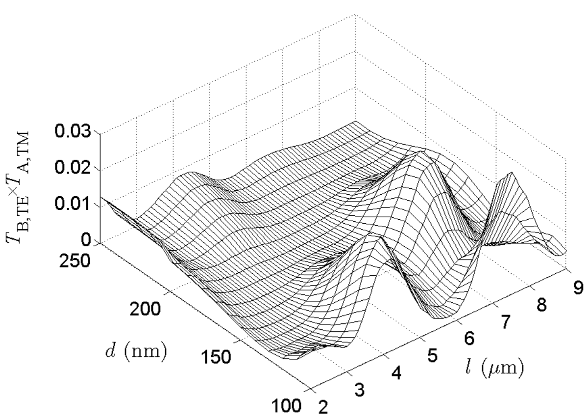
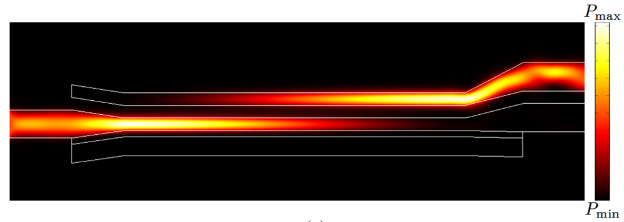
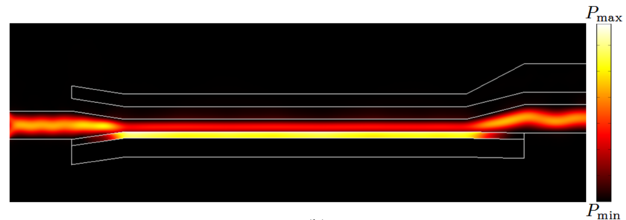


Figure 2. $T_{\mathrm{B,TE}} \times T_{\mathrm{A,TM}}$ product versus separation distance d and straight section length l at $w_{\mathrm{A}} = w_{\mathrm{B}} = 200$ nm.



(a)



(b)

Figure 3. Time-average power flow of the optimized plasmonic-mode-assisted polarization splitter for (a) TE and (b) TM modes at $\lambda_0 = 1550$ nm. The insertion loss is < -0.14 dB for the TE and < -0.32 dB for the TM.

TABLE I
PERFORMANCE OF THE PRESENT POLARIZATION SPLITTER

Figure of Merit	$\mathrm{SR_{TE}}$	$\mathrm{SR_{TM}}$	$\mathrm{ER_{thru}}$	$\mathrm{ER_{cross}}$
$+30\%$ error in width	10.70	18.11	11.13	17.69
Optimized structure	20.73	22.54	20.55	22.71
-30% error in width	12.64	17.55	12.14	18.05

IV. Summary

An ultra-compact DC-based polarization splitter in asymmetric metal/multi-insulator configuration with a critical dimension of 100 nm has been presented. A large modal birefringence of about 0.7 enables a clean separation of TE and TM modes within one TE coupling length. The footprint of the device, including the input/output tapers, is $7.28 \times 1.60\ \mu\mathrm{m}^2$ and the 10-dB fabrication tolerance could be up to $\pm 30\%$ of the targeted widths of Si waveguide and silica gap region.

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