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Design and analysis of optical coupler with a stable splitting ratio based on cascaded multistage directional couplers

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Abstract. An optical 3 dB coupler based on cascaded three-stage directional couplers is proposed. The optical coupler with a finite impulse response on optical power is able to provide a stable 50% splitting ratio. The influence of the waveguide gap, width of each waveguide, and coupling length on the performance of the proposed coupler is illustrated. The numerical analysis and results show the reported coupler with less sensitivity to such fabrication variations. The proposed optical coupler could also be designed with any stable splitting ratio for optical communication applications. © 2012 Society of Photo-Optical Instrumentation Engineers (SPIE). [DOI: [10.1117/1.OE.51.9.094603](https://doi.org/10.1117/1.OE.51.9.094603)]

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1 Introduction

Dense wavelength division multiplexing (DWDM) components and systems attract much attention in optical communication applications, mainly because of the increasing volume of and demand for data transmission in optical networks. Most DWDM components, such as interleaver filter, thermo-optic switch, array waveguide grating, and add-drop multiplexer, etc., were fabricated through planar lightwave circuit (PLC) technology and implemented in the applications of waveguide-type devices.¹⁻⁸ In these waveguide-type devices, the 3 dB coupler plays the important role of providing the optical power splitting and combining. Therefore, waveguide-type devices can precisely demonstrate specific functions, such as spectrum filtering and optical power switching. For example, a lattice-type waveguide interleaver filter composed of cascaded Mach-Zehnder interferometers (MZIs),²⁻⁵ thermo-optical switches with a double-MZI configuration,⁶ and an optical interleaver with ring-assisted MZI structure^{7,8} have been proposed based on the 3 dB silica based coupler to demonstrate compact, low loss, and wide passband filter performance.

A directional coupler has been studied extensively as a 3 dB coupler and is considered as crucial element in the construction of practical PLC devices, by forming two close waveguides. Once two waveguides are brought close together, optical modes of each waveguide either couple or interfere with each other. Hence, the coupling coefficient strongly depends on the coupler device fabrication parameters, such as the gap between two waveguides and width of each waveguide. If a 3 dB coupler within any fabrication variation is applied to optical filter and switches, the prospective characteristics such as the extinction ratio and bandwidth of these optical devices will be severely affected and degraded. There are several approaches reported to reduce the dependence of the power-coupling ratio (splitting

ratio) of 3 dB couplers on the fabrication variations, which are multimode interference (MMI) coupler,⁹ asymmetric directional coupler with two different widths,¹⁰ adiabatic 3 dB coupler,¹¹ curved directional coupler,¹² and multi-stage arrangement by introducing numerous phase differences,¹³⁻¹⁵ respectively. However, MMI couplers and asymmetric coupler are highly sensitive to linewidth and adiabatic couplers are extremely long.

In the present study, scattering matrix with digital signal processing concepts¹⁶ is adopted to implement the proposed optical coupler. The digital or optical filter is usually designed and analyzed to demonstrate a desired magnitude or phase response in frequency domain. Different to the optical filter in the frequency response, the reported optical coupler with a finite impulse response on optical power is able to provide a stable splitting ratio. Therefore, the undesirable coupling or splitting can be avoided and the optical device with less sensitivity to fabrication variations can maintain its performance.

2 Configuration

For the core dimensions comparable with single-mode optical fiber, the large single-mode rib waveguide concept¹⁷⁻¹⁹ is used to design a Si photonic waveguide, shown in Fig. 1. The width (W), inner height (H), and outer regions thickness (h) of the rib are designed to be $2.5 \mu\text{m}$, $2.5 \mu\text{m}$, and $1.6 \mu\text{m}$, respectively. These dimensions have been demonstrated to be an excellent single-mode behavior at an operating wavelength (λ) of $1.55 \mu\text{m}$, within the refractive index of Si guiding layer and SiO_2 layer of 3.5 and 1.45, respectively.

The proposed 3 dB coupler consisting of three-stage 2×2 directional couplers and four optical routes connecting the directional couplers is schematically depicted in Fig. 2. In the proposed structure, the three directional couplers are assumed to have the same design values of power-coupling ratio. The four lengths of optical routes are L_1 , L_2 , L_3 and L_4 , respectively. The scattering matrix with digital signal processing concepts has been explored in the analysis of

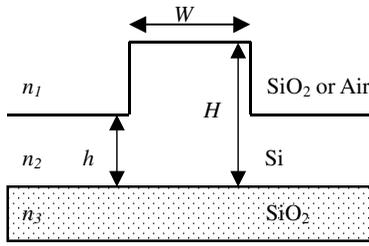


Fig. 1 The large cross section of Si photonic waveguide.

the proposed coupler. The directional coupler element with power-coupling ratio (κ) can be expressed as a 2×2 transfer matrix.

$$\begin{pmatrix} E_1^o \\ E_2^o \end{pmatrix} = \begin{pmatrix} c & -js \\ -js & c \end{pmatrix} \begin{pmatrix} E_1^i \\ E_2^i \end{pmatrix}, \quad (1)$$

where $E_{1,2}^i$ and $E_{1,2}^o$ represent the field amplitudes of input and output light. The through and cross-port transmissions are designated by $c = \sqrt{1 - \kappa}$ and $-js = -j\sqrt{\kappa}$, respectively. The optical routes with length L_1 and L_2 can be express as

$$\begin{pmatrix} E_1^o \\ E_2^o \end{pmatrix} = \begin{pmatrix} e^{-j\beta L_1} & 0 \\ 0 & e^{-j\beta L_2} \end{pmatrix} \begin{pmatrix} E_1^i \\ E_2^i \end{pmatrix}, \quad (2)$$

where β is the propagation constant. Equation (2) is usually expressed as a delay length associated with common path length, which is set equal to the difference in path lengths $\Delta L = L_1 - L_2$. However, for an easy design proposed optical coupler with any designated coupling ratio, the path lengths are used, but not delay lengths. The overall transfer matrix for the present three-stage couplers is the product of matrices as

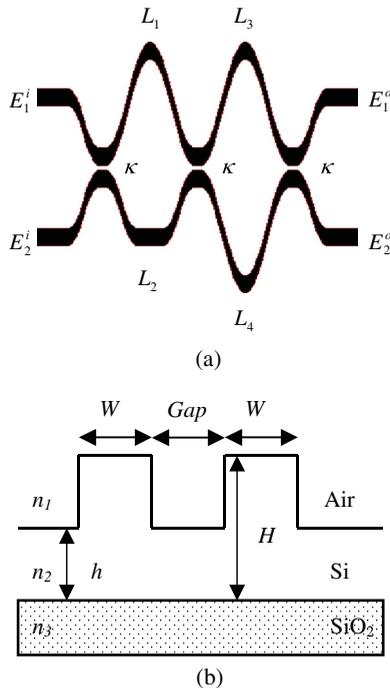


Fig. 2 (a) Schematic configuration of proposed 3 dB coupler. (b) Cross section.

$$\begin{pmatrix} E_1^o \\ E_2^o \end{pmatrix} = \begin{pmatrix} c & -js \\ -js & c \end{pmatrix} \begin{pmatrix} e^{-j\beta L_3} & 0 \\ 0 & e^{-j\beta L_4} \end{pmatrix} \begin{pmatrix} c & -js \\ -js & c \end{pmatrix} \cdot \begin{pmatrix} e^{-j\beta L_1} & 0 \\ 0 & e^{-j\beta L_2} \end{pmatrix} \begin{pmatrix} c & -js \\ -js & c \end{pmatrix} \begin{pmatrix} E_1^i \\ E_2^i \end{pmatrix}. \quad (3)$$

The effective power-coupling ratio (κ_{eff}) of the proposed coupler is defined as:

$$\kappa_{\text{eff}} = \frac{|E_2^o|^2}{|E_1^i|^2} = \frac{P_2^o}{P_1^i}, \quad (4)$$

where P_1^i is the power of incident light and P_2^o is the cross output power. Equation (4) can be derived as:

$$\begin{aligned} \kappa_{\text{eff}} = & (4\kappa^3 - 6\kappa^2 + 3\kappa) + 2\kappa(1 - \kappa) \\ & \cdot \{ (1 - 2\kappa) \cdot [\cos \beta(L_1 - L_2) + \cos(L_4 - L_3)] \\ & + (1 - \kappa) \cdot \cos \beta(L_2 - L_1 + L_4 - L_3) \\ & - \kappa \cdot \cos \beta(L_1 - L_2 + L_4 - L_3) \}. \end{aligned} \quad (5)$$

In a directional coupler, the power-coupling ratio (splitting ratio) varies between 0% and 100% as the coupler length is varied. The reported coupler can also be designed any splitting ratio with a stable range by designing the lengths of four optical routes.

3 Discussions

The low loss Si photonic waveguides are critical for on-chip optical communication applications and have been studied extensively for the past two decades. Large cross section of Si photonic waveguides, within dimensions of 1 to 5 μm exhibit low losses down to 0.3 dB/cm.²⁰⁻²² However, the propagation loss, due to scattering at the rough sidewall, mainly from the etching process is still required to keep as low as possible during the practical device fabrication. The influence of the propagation loss on the splitting ratio and insertion loss of the proposed coupler is illustrated in Fig. 3. The propagation losses of 0.8, 2.4, and 5.5 dB/cm are assumed in terms of recent publications on silicon-on-insulator waveguides,²⁰⁻²² and the no propagation loss waveguide (solid line) is also simulated for comparison. In this paper, the total length of proposed coupler was assumed to be about 0.7 cm. For example of 3 dB coupler, L_1, L_3, L_4 are all 109.95 μm , and L_2 is 109.8 μm . Through the above numerical analysis, the difference of arm lengths is so small that the imbalance of optical loss between the two waveguide arms can be nearly neglected. The total insertion losses are about 0.7, 1.8, and 3.9 dB, respectively, which including the effect of propagation, bending, and waveguide offset. Although the total insertion loss increases, the splitting ratio between the cross-port and the through-port keeps a stable value of 50%. That is mainly due to the 2×2 directional coupler is a symmetric structure and the length difference between two waveguide arms is considerably less. When cascaded multi-stage directional couplers with special delay lengths are used, a finite impulse response on optical power is able to provide a stable splitting ratio.

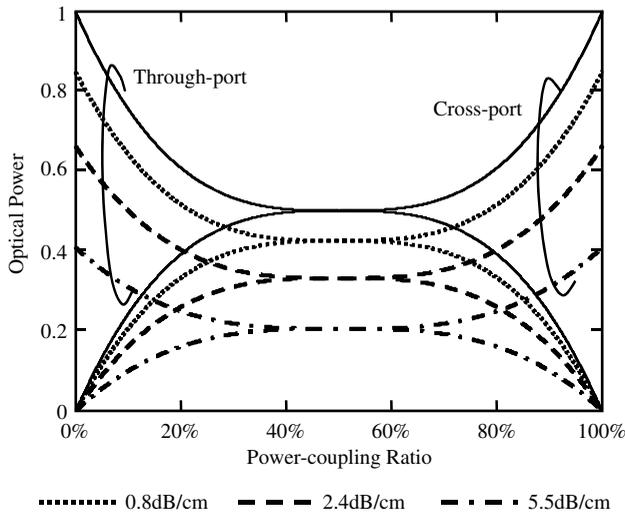


Fig. 3 Simulated optical power of the proposed 3 dB coupler at both cross-port and through-port with different propagation losses.

The relationships between the effective power-coupling ratio (κ_{eff}) and the individual coupling ratios (κ) are shown in Fig. 4. Any power-coupling ratio (splitting ratio) can be achieved by designing the lengths of four optical routes, and the value can be calculated by using Eq. (5). For example, a 3 dB coupler (50% splitting) is assumed that the length difference of $L_1 - L_2$ is $\lambda/3$, $L_3 - L_2$ is $\lambda/3$, and $L_4 - L_2$ is $\lambda/3$, respectively, where λ is the operating wavelength as the same defined above of $1.55 \mu\text{m}$. The behavior of the κ_{eff} can maintain a stable value of 50% at the range of κ from 39.2% to 60.8%. Such a 3 dB coupler design significantly increases the fabrication tolerance on power-coupling ratio by about $\pm 21.6\%$ more than a directional coupler. The length differences of $L_1 - L_2$, $L_3 - L_2$, and $L_4 - L_2$ for 95% splitting are $\lambda/3$, $\lambda/8$, and $\lambda/3$. The length differences of $L_1 - L_2$, $L_3 - L_2$, and $L_4 - L_2$ for 72% splitting are $\lambda/3$, $\lambda/4$, and $\lambda/3$. The length differences of $L_1 - L_2$, $L_3 - L_2$, and $L_4 - L_2$ for 28% splitting are

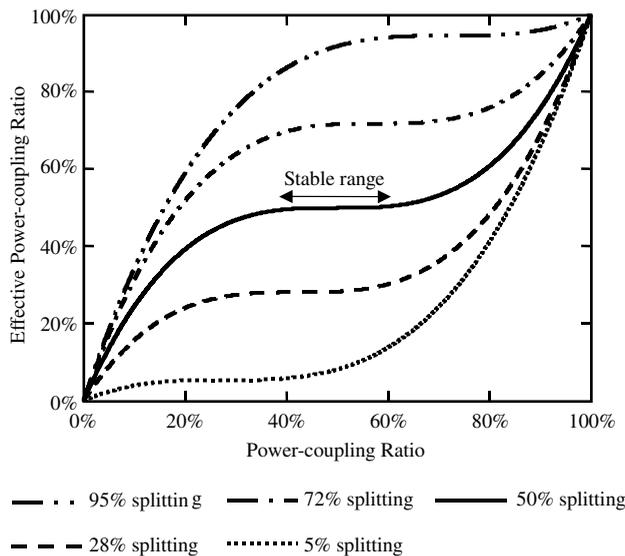


Fig. 4 Simulated effective power-coupling ratios with the individual power-coupling ratio.

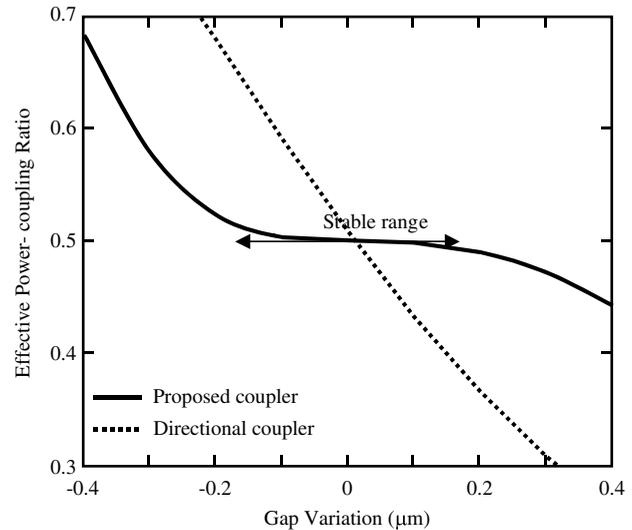


Fig. 5 The simulated κ_{eff} of a 3 dB coupler is plotted as the waveguide gap variation within a gap of $1 \mu\text{m}$.

$2\lambda/3$, $\lambda/4$, and $\lambda/3$. The length differences of $L_1 - L_2$, $L_3 - L_2$, and $L_4 - L_2$ for 5% splitting are $2\lambda/3$, $\lambda/8$, and $\lambda/3$. The propagation loss is assumed 0.3 dB/cm.

At the present study, the power-coupling ratio of directional coupler is shown to be a strong function of coupling coefficient and coupling length.²³ The coupling coefficient of a directional coupler depends exponentially on the gap between two waveguides because the coupled evanescent field decreases exponentially. In order to demonstrate the proposed coupler with a stable splitting ratio, beam propagation method numerical analysis was carried out to obtain the influence of the waveguide gap variations, the coupling length and the waveguide width variations. In Fig. 5, the effective power-coupling ratio of a 3 dB coupler is plotted as the waveguide gap variations, where the width of Si rib waveguide is $2.5 \mu\text{m}$, and the gap between waveguides is $1 \mu\text{m}$. The directional coupler (dotted line) shows a sinusoidal functional behavior on κ_{eff} with waveguide gap variation (fabrication fluctuation). Therefore, in the presence of the waveguide gap variation, the power-coupling ratio is severely affected and moves far away from its designed value of 0.5 (50% splitting). However, the proposed 3 dB coupler (solid line) has a flat range of the κ_{eff} around 0.5. The κ_{eff} varies about $\pm 3\%$ at the waveguide gap variation of $\pm 0.2 \mu\text{m}$, but the κ_{eff} of the directional coupler varies around $\pm 30\%$. Thus the proposed 3 dB coupler demonstrates a significant improvement on power-coupling ratio to waveguide gap variations $\pm 20\%$ at the gap width of $1 \mu\text{m}$.

In Fig. 6, the effective power-coupling ratio is calculated as a function of the normalized coupling length, where the coupling length is about $550 \mu\text{m}$ at the gap of $1 \mu\text{m}$. The ideal normalized coupling length of the directional coupler is one-half when the power-coupling ratio is 0.5 (50% splitting). The κ_{eff} of the proposed 3 dB coupler (solid line) varies about $\pm 1\%$ at this stable range of the normalized coupling length from 0.431 to 0.569 and the κ_{eff} of the directional coupler (dotted line) varies $\pm 21\%$ in comparison. Therefore, a significant increase of fabrication fluctuation on the coupling length can be realized for the proposed coupler in contrast to the directional coupler.

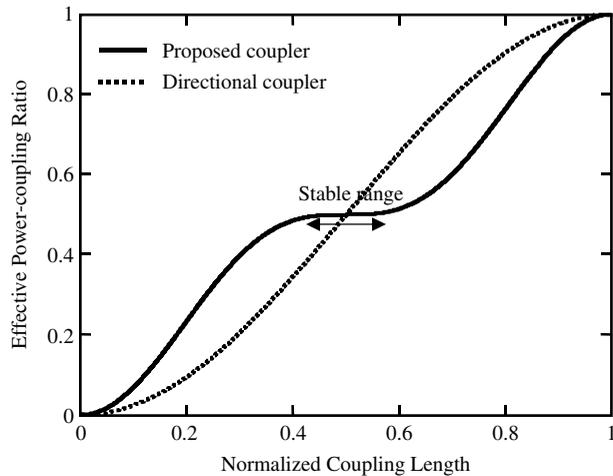


Fig. 6 Simulated effective power-coupling ratios with normalized coupling length.

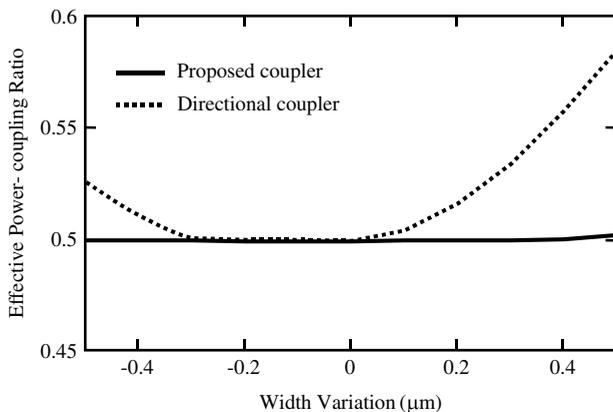


Fig. 7 Simulated effective power-coupling ratios of a 3 dB coupler with the width variation.

The influence of the width variations on the effective power-coupling ratio is shown in Fig. 7. The effect of width in this waveguide structure is not severely like the gap of waveguide and the coupling length. However, our proposed coupler, for example a 3 dB coupler, also has a stable value of 50%.

4 Conclusions

In this paper, we proposed an approach to have a stable splitting ratio by implementing multi-stage directional couplers. The finite impulse response is used on optical power, but not in frequency response. The numerical simulations have shown the power-coupling ratio of the proposed coupler is less sensitive to fabrication fluctuation. A significantly wider stable range on the power-coupling ratio in the presence of fabrication fluctuations, such as waveguide gap variation, and coupling length variation, and width of each waveguide, is illustrated through this study. The proposed optical coupler could be considered as a potential component for application in other optical waveguide devices.

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