Wavelength-insensitive and Lossless 50:50 Directional Coupler Based on Silicon Bent Waveguides

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A broadband 50:50 bent directional coupler, based on low loss bends, is experimentally demonstrated to significantly reduce coupling variation from 0.369 in the traditional directional coupler to just 0.076 over an 80 nm wavelength range, showcasing a substantial 4.85 times less coupling variation.

***Index Terms*—Silicon Photonics, broadband splitter, lossless**

Directional couplers (DCs) play a pivotal role in silicon photonics with versatile applications such as power splitting, modulation, and wavelength division multiplexing. However, inherent wavelength dependency due to dispersion poses a bandwidth limitation for the use of DCs. In particular, a 50:50 DC achieves this ratio only at one wavelength. This unintended coupling variation significantly degrades the performance of many silicon photonics applications. In the quest for achieving a broadband 50:50 DC, diverse schemes have been explored. Notably, adiabatic DCs based on mode evolution have been proposed where the light in the input waveguide evolutes adiabatically to an even or an odd mode in the DC resulting in 50:50 splitting [1]. Adiabatic DCs are, however, inherently long devices that could be longer than 300 μm and often exhibit high excess loss. Another design strategy employs asymmetric DCs, utilizing waveguides of different widths to reduce wavelength dependency. Despite their potential, these designs are highly sensitive to linewidth variation and are fabrication intolerant [2]. Achieving broadband functionality and fabrication tolerance poses a significant challenge in silicon photonics, primarily due to the nanoscale dimensions and the high index contrast [3]. Recently, bent DCs, a subset of asymmetric DCs, have emerged as a viable solution [4]. They offer broadband coupling, a relatively compact footprint, all while maintaining high fabrication tolerance. The introduction of asymmetry through bent waveguides eliminates the need for different waveguide widths, and therefore addresses the fabrication sensitivity observed in DCs with asymmetric waveguides widths. Due to the asymmetry, full power transfer is not possible anymore, in contrast to coupling in a symmetric straight DC, which results in non-monotonic coupling with wavelength, and could be engineered to achieve a maximum coupling around 50%, ensuring broadband behavior [4]. In this work, a broadband 50:50 DC based on bent waveguides is presented, utilizing low loss bends that we demonstrated in an earlier study to diminish any excess loss caused by the bends [5]. The proposed lossless 50:50 DC is experimentally demonstrated with a mere 0.076 coupling variation over 80 nm wavelength range as compared to 0.369 variation for the traditional DC design.

According to coupled mode theory, the cross coupling ratio can be expressed as

$$\kappa^2 = A\sin^2(kx+\phi), \tag{1}$$

while the thru coupling ratio is $r^2 = 1-\kappa^2$ in a lossless coupler, where $x = L$ is the coupling length in a straight DC (Fig. 1a), and $x = \theta$ is the coupling angle in a bent DC (Fig. 1b). k denotes the coupling strength per unit length or angle, and A represents the maximum coupling ratio. The

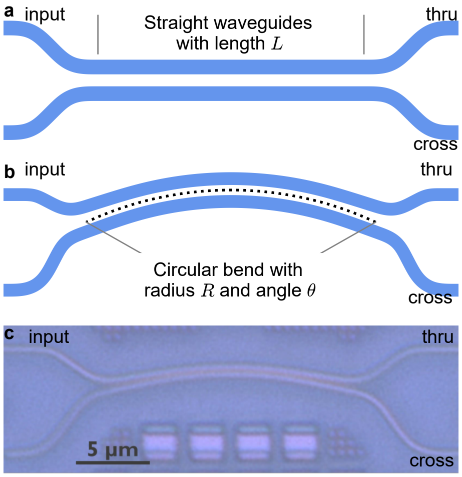

Fig. 1. The schematics of the traditional straight DC with L as the coupling length (a). The schematics (b) and the microscope image (c) of the proposed bent DC with R as the coupling radius, and θ as coupling angle. All the curves are designed with low-loss bends [5]. Waveguide material stacks are SOI with silicon oxide as top cladding, using IMEC iSiPP300 platform. Si thickness is 220 nm, all waveguides widths are 380 nm.

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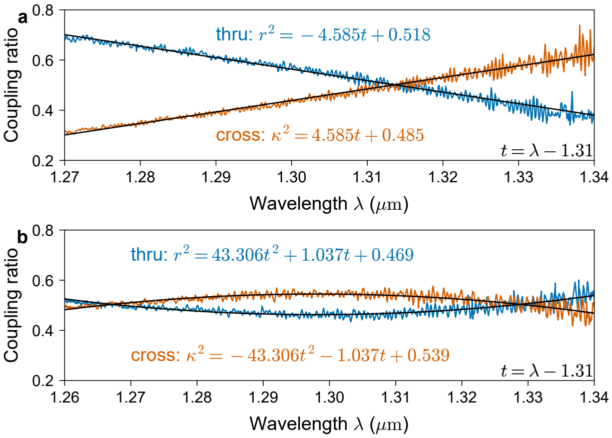

Fig. 2. The measured coupling ratio of the traditional straight DC (a) and the proposed bent DC (b). The straight DC has a coupling gap of 0.15 μm, and coupling length of 6 μm. The colorful lines represent the measured data, while the black curves are the fitted curves.

wavelength dependency ($d\kappa^2/d\lambda$) can be expressed as

$$\frac{d\kappa^2}{d\lambda} \approx \frac{dA}{d\lambda}\sin^2(kx+\phi) + \frac{dk}{d\lambda}Ax\sin(2kx+2\phi). \quad (2)$$

A has negative correlation with the phase mis-matching $|n_{eff1} - n_{eff2}|$, where n_{eff1} and n_{eff2} denote the individual effective refractive indices of the two waveguides being coupled respectively. $k = \pi(n_{eff,even} - n_{eff,odd})/\lambda$ where $n_{eff,even}$ and $n_{eff,odd}$ denote the effective refractive indices of the even and odd super modes in the DC respectively. Note that the effective refractive indices related to bent waveguides should be calculated with Maxwell equations expressed in cylindrical coordinate system. To minimize the DC wavelength dependency, both $|dA/d\lambda|$ and $|dk/d\lambda|$ should be minimized. Notably,

$$\frac{dk}{d\lambda} = -\frac{\pi}{\lambda^2}(n_{g,even} - n_{g,odd}) \quad (3)$$

can reach 0 by properly designing the parameters in a bent DC, where $n_{g,*} = n_{eff,*} - \lambda\partial n_{eff,*}/\partial\lambda$ (* is even or odd). Therefore, the wavelength-insensitive DC design can be derived as an optimization problem

$$\begin{aligned} \min_{g,R,\theta} \quad & \left|\frac{\partial n_{eff1}}{\partial\lambda} - \frac{\partial n_{eff2}}{\partial\lambda}\right| \\ \text{s.t.} \quad & n_{g,even} - n_{g,odd} = 0 \end{aligned} \quad (4)$$

where g is the coupling gap, R is the coupling radius, and θ is the coupling angle. Guided by Eq. 4, a wavelength-insensitive bent DC is achieved with $g = 0.1$ μm, $R = 25$ μm, and $\theta = 8.5$ °. The fabricated device is illustrated in Fig. 1c. All the bends in the design are low loss bends that we demonstrated in an earlier study [5], where the bends have both continuous curvature and curvature derivative at all connections.

As shown in Fig. 2a, the coupling ratio of the traditional straight DC shows linear dependency with the wavelength, $d\kappa^2/d\lambda = 4.59$ μm^{-1}. In contrast, the coupling ratio of the proposed bent DC (Fig. 2b) follows a second order polynomial relationship with the wavelength. This polynomial plateaus at $\kappa^2 \approx 0.5$ where $d\kappa^2/d\lambda$ is substantially reduced to zero around $\lambda = 1.3$ μm enabling the broadband behavior of the coupler. Within the measured 80 nm wavelength range, the coupling variation of κ^2 is merely 0.076, which is 4.85 times lower than the straight DC. Compared to the results existing in literature (Tab. I), the proposed splitter has the least coupling variation within the measured wavelength range of 80 nm. Moreover, no significant excess loss of the proposed bent DC was observed.

TABLE I
PERFORMANCE COMPARISON OF 50:50 SPLITTERS.

Reference	Structure	Coupling variation (over 80 nm)	Excess loss (dB)
[1]	Adiabatic DC	> 0.1	-
[2]	Asymmetric DC	0.11	< 1
[6]	Bent DC	0.13	< 1
[7]	Bent DC	0.18	-
[8]	Bent DC	0.106	0.05
This work	Bent DC	0.076	~ 0

In conclusion, an optimization model is derived for wavelength-insensitive DC design with bent waveguides. On this basis, a broadband 50:50 splitter is experimentally demonstrated with a drastic reduction in wavelength dependency, where the coupling variation of the proposed 50:50 DC is merely 0.076 within 80 nm wavelength range, which is 4.85 times better than straight DC, and also outperforms all existing broadband DC designs to our best knowledge. Moreover, all bends in the proposed design are implemented with low loss bends, enabling lossless coupling.

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