Multiport optical power splitter design based on coupled-mode theory

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Abstract. We proposed a multiport T-shaped 1 x 8 balanced optical power splitter design based on asymmetric vertical silicon slot waveguides working on the principle of coupled-mode theory (CMT). The scheme of the power splitter is unique which offers strong field confinement of TE-polarized light and delivers the light to four ports each on two opposite side of the chip. By shifting the slot towards the outer sideline of the bend, the bending losses are reduced to 80% as compared to standard symmetric slot waveguide.

1. Introduction
Silicon photonics has become a main area of research and development in terms of micro and nanometer scale optoelectronic devices [1]. Optical power splitters (OPSs) are vital components for splitting and combining the optical signals, which have gathered great consideration in integrated photonic systems [2-5]. There is an increasing demand for these optical elements in the field of integrated optics [6-8] which offer low cost and compact size. Recently, several different types of OPSs designs are investigated, which are typically based on Y-branch [9], multi-mode interference (MMI) [10], photonic crystal [11], and sub-wavelength plasmonic waveguide (WG) [12].

In this article, we put forward the design of a 1x8 OPS based on asymmetric vertical slot waveguides (AVSWG). The working principle of this component is based on the coupled-mode theory [13, 14]. The physical models for coupled-WG systems comprise of two or more optical WGs positioned in close vicinity which can be parallel to each other with irregular separations. The coupled-mode equations are given as follows:

\[ \frac{dA_1}{dz} + j\kappa A_1 \exp(-j\Delta \beta z) = 0 \]  

\[ \frac{dA_2}{dz} + j\kappa A_2 \exp(+j\Delta \beta z) = 0 \]

Where \( A_1 \) and \( A_2 \) are the local amplitudes of the modes in WG1 and WG2, respectively. The change in \( A_1 \) is related to the \( A_2 \) through the coupling coefficient \( \kappa \) and vice-versa. \( \Delta \beta \) indicates the mismatch in propagation constant between the WGs. This means that the mode amplitudes are coupled together. The coupling coefficient is conceivably the main parameter of the coupler. The main condition for \( \kappa \) to be high is that the evanescent tail of the E-field penetrates WG 1 to a great amount. For that reason, it is acknowledged that \( \kappa \) is most strongly affected by an inter-WG gap (g), which should be small.
A slot WG is an exceptional structure that allows the light to be strongly confined and guided inside a nanometer-scale region of low index material (slot) surrounded by high index material (rail) from both sides [15, 16]. The discontinuity of the E-field perpendicular to the interface between materials with the low and high refractive index results in strong light confinement in a slot. There are many benefits associated with this unique WG structure such as a small beat length of the guiding light and strong optical confinement in the slot region that results in remarkably low losses. Besides, CMOS compatible materials and technology can be utilized in the fabrication of slot WGs [17].

2. Device design
We suggested a T-shaped 1x8 OPS splitter design based on 90° bend AVSWGs simulated by using the finite element method (FEM). To estimate an open geometry, scattering boundary conditions are applied at the outer edges of the FEM simulation window. The OPS design is optimized at 1550 nm telecommunication wavelength. The refractive index value of Silicon (n_{Si}) and sapphire (n_{SiO2}) used in the simulation is 3.47 and 1.44 at 1550 nm, respectively. The schematic of a 1x8 OPS is presented in figure 1. The OPS design is optimized in different steps so that same amount of power is transferred to each port, i.e 12.5%.

![Figure 1. The layout of a 1x8 OPS based on AVSWGs.](image)

3. Power confinement factor in slot WG
Prior to 1x8 OPS design, the geometric parameters of AVSWG are optimized. These WG structures are polarization-dependent, therefore, quasi- TE polarization is utilized to obtain a guided mode. Thus, the height (H_{WG}) of the AVSWG is less significant. By optimizing the geometric parameters, the maximum confinement is obtained at the WG parameters of W_{WG}= 450 nm by using H_{WG}= 220 nm in a slot of 40 nm. To calculate the optimal distance between bus WG and corresponding WGs, g is varied in order to acquire the equal power transfer between Out 1 and Out 3. Here, we assume that OPS design is symmetric where left-side is identical to the right-hand side, therefore power distribution between Out 1= Out 5 and Out 3= Out 7. Besides, special care should be taken while selecting g so that WGs should not be perfectly coupled. Some proportion of power should reside in the bus WG to travel and later on couples to Out 3 and Out 7. However, the power distribution can be controlled by varying the coupling length. For that reason, we choose g=120 nm as an initial value for our design.

4. Optimization of the interaction length of a balanced 1x4 OPS
The interaction length (L1 and L2) of slot WGs linked to a bend WGs has a critical role in coupling the main portion of light from one WG to another. Prior to 1x8 OPS, we need to optimize the
geometric parameters of balanced 1x4 OPS. In this point the precise choice of L1 and L2 is essential. When L1=L2, the major proportion of power is coupled to out 1 and out 5 through bend WG's while the remaining insignificant power couples to out 3 and out 7 which results in imbalance OPS design. Contrary to this, we have to optimize L1 where half of the power should couple to ou 1 and out 5 and the other half should remain in the bus WG and couples to out 3 and out 7. The length of out 1, out 3, out 5 and out 7 is denoted as L3 which is maintained at 2200 nm. The condition for a balanced 1x4 OPS is satisfied for L1 and L2 at 80 nm and 1500 nm, respectively.

5. Reduction of bending loss
To reduce the bending loss of the symmetric vertical slot WG, the displacement of slot towards or away from the bend is suggested. The total width of WG is fixed at 340 nm together with slot of width 40 nm. The slot is moved towards and away from the bend by keeping the total width of the WG constant and observes the divergence in the output power. By doing so, the E-field confinement in the slot increases due to the maximum overlap of the two evanescent tails of the high index WG in the left cladding region. As a result, the bending loss is reduced. The loss tends to decrease as the slot shifts toward or away from the bend but there is a finite limit to relocate the slot. The minimum loss of 2.41 dB is calculated at 115 nm slot dislocation towards the outer periphery of the bend. The dependence of bending loss on the slot displacement is shown in figure 2.

![Figure 2. Dependence of bending loss on slot displacement.](image)

![Figure 3. Power distribution in 1x8 OPS design versus g1.](image)
6. Balanced 1x8 OPS design
In the preceding sections, a balanced 1x4 OPS design is obtained. Now, we are introducing two bridge WGs and two supplementary ports on each side of the bus WG to further split the power. Bridge WG is used to provide a suitable gap between the respective output ports. The length of the out 2, out 4, out 6 and out 8 is maintained at 1800 nm while the length of bridge WG is fixed at 1000 nm. L4 is rather smaller than L3 which provides a considerable distance for a mode to propagate in L3 prior to coupling to the bridge WG. The balanced power distribution ratio is acquired at g1= 50 nm with a slight fabrication error of ±5 nm as shown in figure 3. The contour plot of the left side of the 1x8 OPS is plotted in the inset of figure 3. The line graph of a 1x8 OPS is presented in figure 4 which is obtained by cutting the output ports on both sides of the chip at (Hw/2) and acquired an E-field distribution at the output ports 1,2,3,4,5,6,7 and 8.

![Output cross-section (µm)](image)

**Figure 4.** Line graph of a balanced 1x8 OPS.

7. Concluding remarks
We proposed a novel design of T-shaped 1x8 balanced optical power splitter based on asymmetric vertical slot waveguides. The scheme of the design is distinctive which supply four output ports each on two opposite sides of the chip. The bending loss of the waveguides is reduced to 80% as compared to symmetric slot waveguide by moving the slot in the direction of the outer periphery of the bend. Based on this study, splitters with different power distribution ratio can be realized by varying the inter-waveguide gap.

8. References
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