Compact and Alignment-Tolerant Vertical Coupler for Heterogeneous Photonic Integration

(Student paper)

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We present a generic design method of compact and alignment-tolerant vertical coupler for III-V-on-silicon photonic integrated circuits. Based on a multi-segmented tapered structure, our coupler (87 µm long) is almost 3-fold shorter than the state-of-the-art adiabatic couplers but still outperforms with a < 0.3 dB coupling loss (i.e., > 94% efficiency) with ± 1.0 µm misalignment, making it suitable for commercially available assembly tools, such as micro-transfer printing and flip-chip bonding.

Keywords: *Heterogeneous integration, vertical coupler, compact, alignment-tolerant.*

INTRODUCTION

III-V-on-silicon heterogeneous integration enables a variety of active photonic devices, such as SOAs and lasers, to be integrated with Si photonics circuits. Among diverse integration techniques, flip-chip bonding and die/wafer bonding are widely used thanks to their high technical maturity. The former allows the III-V devices to be pre-processed/tested yet suffers from limited integration densities and strict coupling requirements, while the latter supports dense integration but demands modifications on the silicon photonics back-end flow [1]. Recently, micro-transfer-printing (µTP) arose as a newcomer in the field. By parallelly transfer printing III-V coupons onto silicon platforms, it combines the advantages of flip-chip bonding and die/wafer bonding without disturbing the process on the silicon photonics side [2].

The vertical coupler is a key building block for heterogeneous integration as it enables the power transition between the III-V and silicon layers. The tolerance to lateral misalignment is essential for vertical couplers. For example, the 3σ alignment accuracy for current µTP tools ranges from ± 0.5 to ± 1.5 µm, which, with further development, is expected to be ± 1.0 µm for large-array transfer printing, setting a benchmark for the coupler design [3]. The compactness of vertical coupler is also of great importance, especially for applications like optical switches and optical processors where massive III-V components are densely integrated at chip-level. However, it is non-trivial to achieve both metrics. Based on different working principles, vertical couplers can be classified as resonant couplers or adiabatic couplers. Utilizing the periodic interference phenomena between the coupled waveguides, resonant couplers can be rather short but always sensitive to alignment/fabrication variations [4]. Adiabatic couplers, in contrast, rely on gradual changes in the device structure to slowly transfer the power into target waveguide, which relaxes the alignment/fabrication control but requires hundreds of microns in length to ensure the adiabatic condition [5]. To solve this dilemma, we propose a compact and alignment-tolerant vertical coupler with multiple tapered segments on the basis of resonant coupling mechanism. The device is 87 µm long and has a < 0.3 dB coupling loss even when ± 1.0 µm misaligned, which, to our best knowledge, is a new record for heterogeneous III-V-on-silicon vertical couplers.

RESULTS

Our design is demonstrated based on an exemple III-V-on-silicon heterogeneously integrated system (detailed layer information can be found in [5]), where the III-V component is located on top of a 400 nm silicon rib waveguide with a lateral misalignment Δm, as shown in Fig. 1(a). The mode propagation and interaction in such coupled-waveguide system can be described by the coupled mode theory, as [6]:

$$\frac{d}{dz}\begin{bmatrix} a_1 \\ a_2 \end{bmatrix} = \begin{bmatrix} -i\beta_1 & -i\kappa \\ -i\kappa & -i\beta_2 \end{bmatrix}\begin{bmatrix} a_1 \\ a_2 \end{bmatrix}, \tag{1}$$

where a_1 and a_2 represents the the mode amplitudes in the uncoupled III-V and Si waveguides, while β_1 and β_2 are their propagation constants, respectively. z denotes the propagation direction. κ is the mode coupling coefficient, defined as:

$$\kappa_{ij} = \frac{k_0^2}{2\beta}\iint (n^2 - n_j^2)\psi_i\,\psi_j^* dxdy, \tag{2}$$

where ψ_i and ψ_j are the normalized eigenmodes in each uncoupled waveguide, β is the mode propagation in the coupled waveguide, k_0 is the free-space propagation constant, and n, n_i, and n_j are the refractive index profiles of the coupled waveguide and two uncoupled waveguides, respectively. It can be derived from Eq.(1) that the optical mode beats periodically between the two waveguides (assmuing κ to be constant) and reaches its first maximum at $z = \pi/2\kappa\sqrt{1+\gamma^2}$, where $\gamma \equiv (\beta_2 - \beta_1)/2\kappa$, with a transferred power of $1/(1+\gamma^2)$. Hence, to design a conventional resonant coupler with no coupling loss, its length should be set as half the mode beating period, while the waveguide widths need to be well chosen to make sure that γ is 0 (i.e., β_2 should be equal to β_1, known as the phase matching condition). Nevertheless, misalignments can significantly weaken the coupling strength (i.e., reduce the value of κ) so that the coupler no longer cuts off at the point of maximal power transition. To mitigate such sensitive dependence on the coupling length, one viable way is to use tapered structures to break the periodical resonant behavior, as reported in [7]. Thus, in our case, we first propose a vertical coupler based on sharp linear tapers, and then extend it to a multi-segmented tapered structure to enhance the performance, as shown in Fig. 1(b-c). Detailed analysis of the two designs are presented successively as follow.

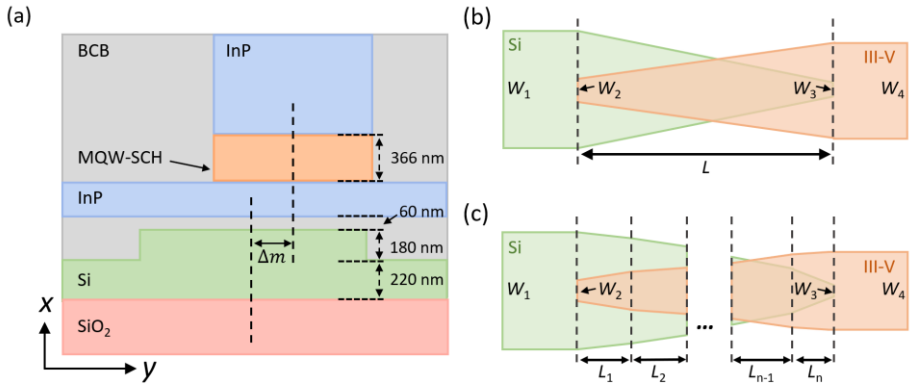

Fig. 1. (a) Cross-section schematic of a III-V-on-silicon vertically coupled-waveguide system [5]. (b-c) Top view of the proposed vertical couplers with linearly tapered structure and multi-segmented tapered structure, respectively.

The geometry of the linearly tapered structure is determined by the widths W_1 to W_4 and length L, where the tip widths W_2 and W_3 are set to be 0.5 µm and 0.2 µm, respectively, considering the fabrication limitations on critical dimensions. Our optimization strategy is firstly to select the combination of widths W_1 and W_4, and then sweep the length L to search for the best alignment tolerance. As there are only three parameters, this process can be done via a brute-force search that the optimal combination of W_1 and W_4 is found to be 3.35 µm and 2.95 µm, respectively. Figure 2(a) shows the calculated map of γ for different width combinations of the III-V and silicon waveguides when misalignment is 1.0 µm, in which the width combination of the optimized linearly tapered structure is illustrated by the white-dashed line. Figure 2(b) shows the simulated efficiencies versus length L at different misalignment levels. Under perfect alignment, the coupling efficiency reaches the peak when L is 52 µm and keeps high with increasing taper length, illustrating the suppression of the periodic coupling phenomenon. While as the misalignment increases, a longer taper length is required, e.g., L needs to be 93 µm to achieve a < 0.4 dB loss when 0.6 µm misaligned, which indicates that a better alignment tolerance can be realized by properly lengthening the taper. However, when the misalignment increases further, the coupling efficiency dramatically deteriorates even with a longer taper length. This can be explained by the simple fact that there is only one point in the linearly tapered structure that is perfectly phase matched ($\gamma = 0$) while all other parts are mismatched, especially at the beginning and the end where the absolute value of γ is on the order of ten, as shown in Fig. 2(a).

Thus, to obtain better performance, a tapered structure with varying slopes is proposed that the slopes at its central region where the phase matching can be reasonably satisfied is designed to be gentler than those phase-mismatched peripheral regions. In practice, we adopt a multi-segmented tapered structure. The design procedure also starts with selecting the width combinations for each segment, shown by the red dots in Fig. 2(a) that each two adjacent dots correspond to one specific segment. Most dots are selected around the phase-matched point, following the distribution of the optimal result of the linearly tapered coupler (i.e., the white-dashed line), while at both ends, the dots are adjusted to have smaller values of γ to attain a higher efficiency. As for the lengths of each segment, since it involves a global optimization of multiple parameters, we employ the particle swarm optimization (PSO) algorithm, targeting for the best alignment tolerance with as high efficiency as possible. Note that here, the number of segments is set to be 10 to avoid an overlarge searching space for the algorithm. Figure 2(c) shows the optimized device geometry, which is 87 µm long. As intended, the segments around the central part are more gradual than those on the two sides. Figure 2(d) presents the FDTD simulated results for the multi-segmented

coupler with different misalignments. The coupling loss is only 0.09dB when perfectly aligned, remains < 0.3 dB even with a 1.0 µm misalignment, and drops to 3 dB when 1.2 µm misaligned.

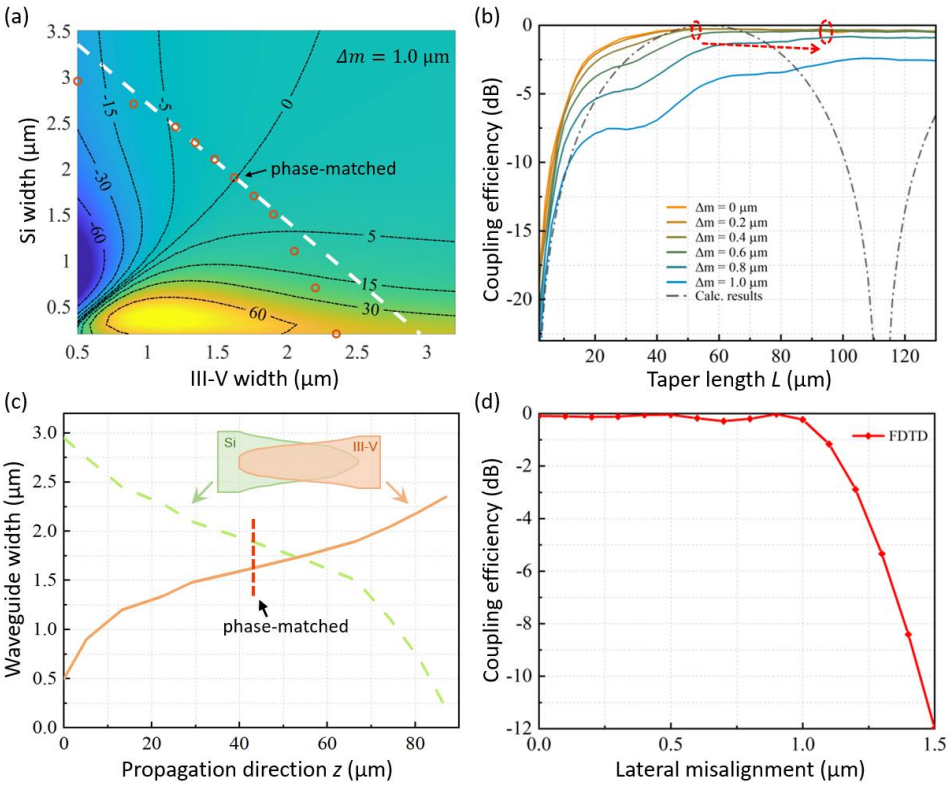

Fig. 2. (a) Map of γ for different waveguide width combinations when Δm is 1.0 µm. (b) Coupling efficiency vs. taper length for the linearly tapered coupler, with a theoretical calculation of conventional resonant coupler plotted for reference. (c) Width variations of the multi-segmented coupler. (d) Coupling efficiency vs. misalignment for the multi-segmented coupler.

CONCLUSION

In this paper, we present a design of a compact and alignment-tolerant vertical coupler based on the resonant coupling mechanism for heterogeneously integrated III-V-on-silicon photonic systems. The coupler structure contains multiple tapered segments, of which the width combinations are carefully selected based on the coupled mode theory, while the lengths are optimized using the PSO algorithm. The device length is 87 µm, nearly 3 times shorter than the state-of-the-art alignment-tolerant adiabatic couplers [5]. Simulation results show that our coupler achieves < 0.3 dB coupling loss even when ± 1.0 µm misaligned, which makes it particularly applicable for those commercially available assembly tools with potential alignment deviations, e.g., micro-transfer printing and flip-chip bonding. The proposed design method can also be applied to different material systems, therefore is expected to find wide applications in various heterogeneous or monolithic integration platforms.

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