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Heterogeneous interconnection of low-loss and dense material platforms using adiabatic tapering coupler

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Abstract. Recently, we successfully realized amorphous silicon carbide (a-SiC) integrated photonics with optical losses as low as 0.78 dB/cm. Moreover, the deposition of a-SiC was done at 150 °C, which enables successful lift of a-SiC as an additive step to existing photonics circuits. In this work, we present an adiabatic taper coupler which provides bidirectional lossless connection between two integrated photonics platforms: thin-film silicon nitride (Si_3N_4) and a-SiC. Normalized power transmission of 96.61% is presented, and the coupler enables strong confinement when coupling from weakly confined thin-film device to normal thickness device. By utilizing such a coupler as bridge, switching back and forth between Si_3N_4 and a-SiC platforms can be easily realized. This allow us to carry out applications including quantum interference and digital Fourier spectroscopy, in which long optical delay lines are constructed on Si_3N_4 and highly integrated circuits are built on a-SiC.

1 Introduction

Traditional silicon based monolithic photonic integration circuits (PICs) is hitting some limits due to the material properties of silicon, for example, comparatively high loss introduced by two-photon absorption (TPA) makes it difficult in large-scale integration and nonlinear optics applications. It has been known that there is not a single material that can address all the needs in PICs, so that currently hybrid/heterogeneous integration is considered as the most compelling solution[1]. Compared to hybrid integration that assembles devices together at packaging level, heterogeneous integration connects various devices composed of different materials on a single chip at fabrication level. It can be regarded as monolithic versatile integration, where the main obstacle is loss control at connecting facets.

Silicon nitride (Si_3N_4) is a low loss material compared to silicon-on-insulator (SOI) platform. With specific designed structures, thin-film Si_3N_4 waveguides provide an ultra-low loss of ~1 dB/m. Thus it is suitable for long propagation distance required applications such as optical delay lines[2, 3]. On the other hand, Si_3N_4 has a relatively low refractive index of 1.98 and is expected to impose relatively weak constraints on propagating mode as waveguide. Amorphous silicon carbide (a-SiC) that deposited with plasma-enhanced chemical vapour deposition method holds a refractive index of 2.45, Kerr nonlinear coefficient of 4.8×10^{-14} cm/W, which is a novel platform that already showed its potential in nonlinear optics applications[4]. In addition, microring resonators fabricated and measured in our lab shows an intrinsic quality factor of ~500 thousand, corresponding to optical loss as low as 0.78 dB/cm. Combining such two material platforms holds promise for applications that necessitate long optical delay lines in dense integration. For example in quantum information processing and on-chip digital Fourier transform spectroscopy this kind of combination is inevitable, where lossless Si_3N_4 spirals can be used as optical delay lines, and dense PICs are made in a-SiC platform.

In this work, we propose a low loss adiabatic tapering coupler for heterogeneous PICs, using it as bridge to monolithically incorporate the two promising material platforms of thin-film Si_3N_4 and a-SiC. As a result, bidirectional coupling efficiency of 96.61% is obtained by simulation in Ansys Lumerical FDTD Solutions, and the power decrement at the bending after the coupler is 0.29%, representing that the mode is adiabatically converted.

2 Adiabatic tapering coupler

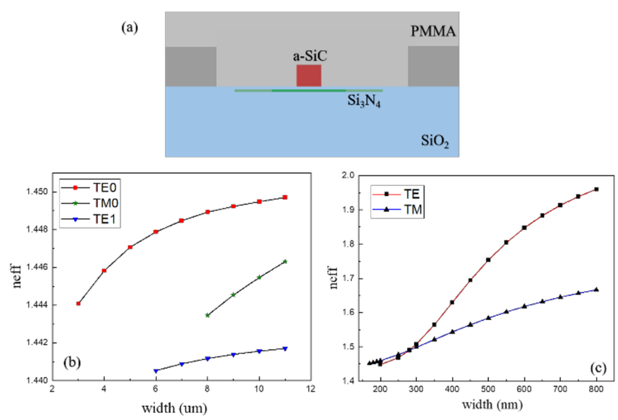

Fig. 1. (a) Device cross-section view. The Effective refractive index varying trend according to the change of (b) thin-film Si_3N_4 waveguide width and (c) a-SiC waveguide width.

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As shown in Fig.1. (a), the coupler is built on silica substrate, covered by PMMA (regions in colour grey) as cladding layer. The red block and green piece of structures are adiabatic a-SiC and thin-film Si_3N_4, respectively. Here, the thickness of thin-film Si_3N_4 tapering waveguide is 40 nm in order to get minimum loss in silicon nitride system, while the thickness of a-SiC tapering waveguide is set to a typical value of 280 nm. The a-SiC taper is placed above thin-film Si_3N_4, and several dozen micron thick silica will form the isolation layer between them to prevent over-etching. Mode profiles and modal effective indices in straight thin-film Si_3N_4 and a-SiC waveguides are analysed in Mode Solutions, shown in Fig. 1. (b) and (c). For thin-film Si_3N_4 waveguide, only fundamental TE mode will be supported if the waveguide width is no larger than 6 μm. In other words, effective index falls into the range of 1.444~1.447 when single mode propagation criterion is satisfied. In adiabatic taper, the effective indices are demanded to match perfectly so as to get minimum loss. Additionally, owing to the huge structural size difference between the two waveguides, mode conversion must be carried out for the same purpose.

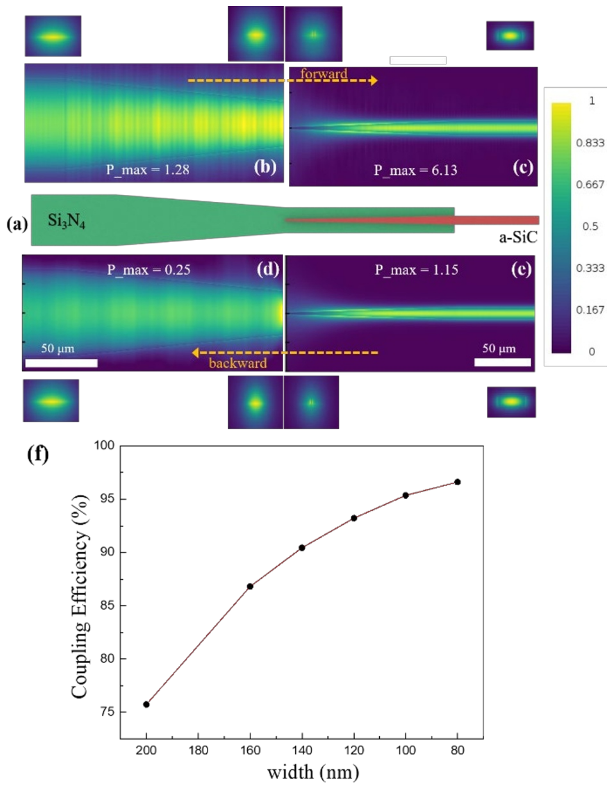

Fig. 2. (a) Device structural diagram. Intensity distribution and mode profiles of the forward direction: (b) and (c), and of backward direction: (d) and (e).

As demonstrated in Fig. 2. (a), a structure in which both a-SiC and thin-film Si_3N_4 tapering down towards the centre is designed to achieve lossless coupling and mode conversion. As mentioned after Fig.1, they are not in a same plane and overlapping with each other at the centre. Normalized field distributions are presented in Fig.2. (b-e), it is evident that the coupler did its job well in both forward and backward propagation directions. Note that the thin-film Si_3N_4 is tapered from 6 μm wide into 3 μm mainly with the aim of compressing the mode area while sacrificing some effective index matching. Relatively, the width of a-SiC decreases from 800 nm to 80 nm to match the effective index. In fact, this process can also be seen in the optimization process shown in Fig. 2. (f). The coupling efficiency reaches 96.61% around 80 nm width, and then increases very little as the width decreases.

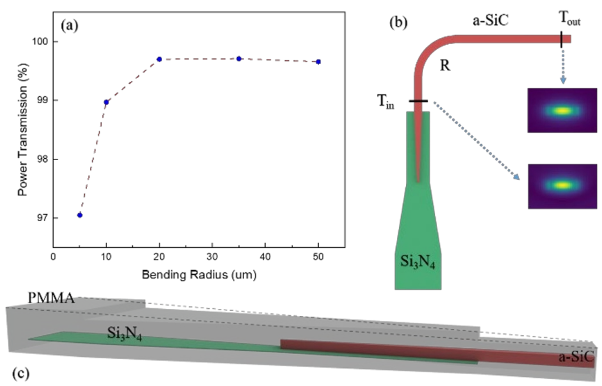

Fig. 3. (a) Normalized power transmission ratio between T_{out} and T_{in}. (b) 90° bend after the coupler. (c) 3D schematic of the coupler with cladding.

Finally, if we consider the forward propagation direction, it is a process of converting a weakly confined mode with large mode area into a strongly confined mode. Therefore, a cladding layer is designed to cover the adiabatic tapering coupler, as illustrated in Fig. 3. (c), the height of the cladding gradually decreases, working as an additional boundary condition on the axis perpendicular to the plane in subfigure (b). To examine it, a 90° bending with several radii is added after the device, which means the bending loss between T_{out} and T_{in} will reveal how strong the confinement is. Consequently, as depicted in Fig. 3. (a), the normalized power transmission exceeds 99.71% at R=20 μm and barely changes as the radius increases. The mode distributions of T_{out} port and T_{in} port are shown in the subplots in Fig. 3. (b), normalized to the same maximum.

3 Conclusion

Based on the a-SiC properties we obtained recently, we report an adiabatic tapering coupler with a coupling efficiency of 96.61%, to connect a-SiC with thin-film Si_3N_4 effectively. It enables highly integrated applications that require long optical delay lines on the same chip, such as quantum integrated photonics and on-chip spectrometry.

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