Sub-1 dB Loss SiN-to-Polymer Waveguide Coupling: an Enabler for Co-Packaged Optics

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Abstract: We report the design, fabrication and characterization of a broadband silicon nitride to polymer waveguide adiabatic coupling interface with sub-1 dB loss around 1310 nm, enabling a sub-2 dB chip-to-chip and chip-to-fiber coupling loss. © 2024 The Author(s)

1. Introduction

Over the past few years, the co-packaging of optics and electronics has gained much interest due to many potential advantages, such as bandwidth capacity and energy efficiency. Since the overall package cost still accounts for 80% of the total photonic package expense nowadays, novel designs are required to reduce this number [1]. As addendum to the integrated CMOS silicon photonics technology, we further promote the use of single-mode (SM) polymer waveguides to couple light between the photonic integrated circuits (PICs) and single-mode fibers (SMF) or other PICs on the same interposer [2]. Similarly to electronic redistribution layers (ERDLs), the SM polymer waveguides act as optical redistribution layers (ORDLs) to further facilitate the co-packaged optics (CPO) technology.

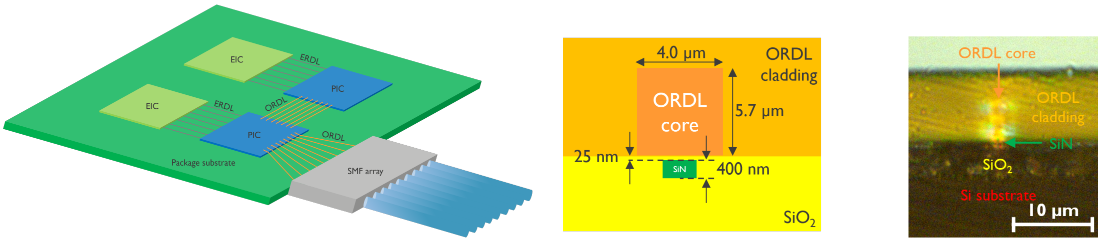
Previously, we proposed the SiN taper design in [3]. In this paper we report on the experimental optical coupling efficiency results by adiabatic light coupling between SiN tapered waveguide and polymer ORDLs, initially designed and then fabricated in an optical packaging setup. We discuss all relevant contributions in the loss breakdown, such as chip-to-fiber losses, SiN and ORDL propagation losses and butt coupling losses.

2. SiN-to-ORDL configuration

The scope of SiN-to-ORDL coupling is demonstrated in Fig. 1a. Several PICs are embedded on an organic package substrate and are electrically connected to EICs by ERDLs. On the other hand, the ORDLs ensure both the optical connection between adjacent PICs as well as the connection to the single-mode fiber array. Fig. 1b schematically displays the cross-section including all relevant dimensions in the configuration. The SiN (tapered) waveguides are formed by Plasma-Enhanced Chemical Vapour Deposition (PECVD) and have a fixed height of 400 nm, while the width varies along the taper starting from the standard width of 710 nm towards 130 nm at the taper tip. The SiN is surrounded by a stack of multiple oxide layers to ensure the mode confinement.

After finishing the PICs in this state, polymer waveguides are deposited on top. This is done by first spin-coating the commercially available EpoCore material (by Micro resist technology [4]). Afterwards, a dedicated lithography mask is used to illuminate the desired polymer waveguides on the PIC. Both the spin-coating parameter recipe and lithography mask have been iteratively finetuned in order to match the optimal ORDL core dimensions. These core dimensions are well-chosen to support a circular Gaussian beam profile for both TE and TM polarizations, as confirmed by Finite-Difference Time-Domain (FDTD) simulations. For the final step, EpoClad is spin-coated to obtain a top cladding layer, to ensure light is confined in the ORDL core. This results in a refractive index contrast equal to 0.5% at λ = 1310 nm (n_{core} = 1.579 and n_{clad} = 1.571). All components are found back in Fig. 1c, showing a microscope cross-section image of the chip's top layer. One can observe the ORDL and SiN core, highlighted by the light travelling through when taking the microscope image.

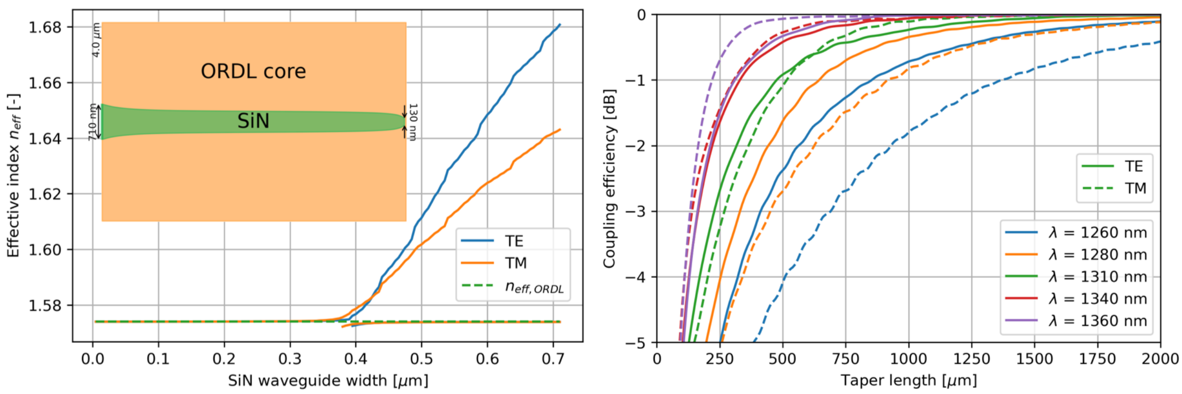
As explained previously in [3], the taper design is based on the phase-matching optimization by continuously monitoring the taper width as function of taper length, as shown in Fig. 2a. This "monotonic mode tracking" (Mono)



(a) (b) (c)

Fig. 1: Visualisation of the SiN-to-ORDL configuration: (a) SiN (tapered) waveguides are located on the embedded PIC(s), while the ORDLs connect the PIC to another PIC and SMF array, (b) Schematic cross-section, including target dimensions, (c) Microscope image indicating all present materials.

ensures the highest coupling between two waveguides, with a specified allowed coupling loss. The expected optical performance is shown Fig. 2b, indicating an expected loss lower than 1 dB for almost all wavelengths for a taper length equal to 1 mm.



(a) (b)

Fig. 2: Lumerical Mode simulation results: (a) The guided mode's effective index varies along SiN width variations; the inset shows the optimal taper shape, (b) SiN-to-ORDL coupling efficiency displays the desired adiabatic behaviour for different O-band wavelengths as function of the taper length.

3. Experimental results

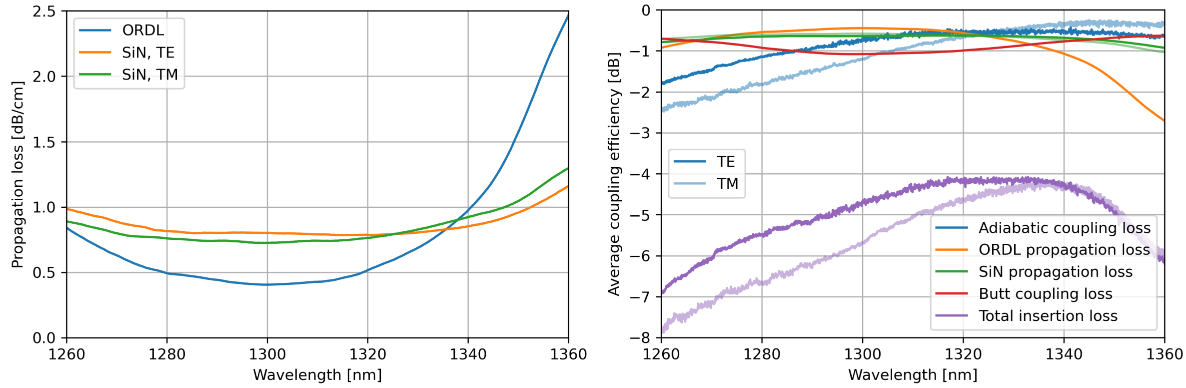
3.1. Propagation loss

We prepared six test samples for the optical characterisation. One of them was selected for the ORDL cut-back analysis while the other five were used to measure the functional test sites that contain the adiabatic tapers. For the ORDL cut-back sample, we only considered the straight ORDL core test sites in the absence of any SiN waveguide or SiN tiles. Once the fiber-to-fiber transmitted power was set as a reference, we iteratively measured the sample and diced it to a smaller length. As a result, Fig. 3a shows the propagation loss for the entire O-band. Around λ = 1310 nm, the propagation loss is less than 0.5 dB/cm, which matches the same values as found in [5]. Additionally, a butt coupling loss of 1 dB was found for each facet.

On the test chips, we also included SiN spirals to examine the SiN (untapered) waveguides. The result is depicted in Fig. 3a, both for TE and TM polarizations. Note that, depending on the polarization, the maximal propagation efficiency reaches a maximum at different wavelength values, but with minimal difference. On the other hand, the SiN propagation losses are close to 1 dB/cm, which is in line with previously reported values [6].

3.2. Adiabatic coupling loss

Fig. 3b summarizes the coupling efficiency for each loss contribution, averaged over 5 test samples. The best taper shape is shown, for a total taper length of 1 mm. The total insertion loss consists of two times butt coupling (fiber-to-ORDL), ORDL propagation over a length of 11 mm, SiN propagation over a length of 8 mm and two times adiabatic coupling (SiN-to-ORDL) for 1 mm long tapers.



(a) (b)

Fig. 3: (a) Propagation loss for SiN and ORDL, (b) Average optical performance for all individual loss contributions are shown, as well as the total insertion loss. Note that the total insertion loss equals two times butt-coupling, ORDL and SiN propagation loss and two times adiabatic coupling loss for 1 mm long ”Monotonic mode tracking” (Mono) tapers.

The experimental results provide evidence for achieving a sub-2 dB chip-to-chip coupling loss, including two adiabatic transitions, and assuming an ORDL propagation distance of less than 1 centimeter. In a similar way, a sub-2 dB chip-to-fiber coupling loss is calculated, taking into account one adiabatic transition, ORDL propagation loss and a sub-1 dB ORDL-to-fiber butt coupling loss.

4. Conclusion

It is demonstrated that 1 mm long SiN tapered waveguides can be designed and fabricated to support adiabatic coupling to polymer waveguides, with less than 1 dB coupling loss covering almost the entire O-band. By combining the low propagation losses for SiN and polymer ORDL, low chip-to-fiber coupling losses, the configuration’s broadband behavior and low polarization dependence, we demonstrate a reliable coupling structure that shows high potential for co-packaged optics integration.

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