Titanium Dioxide Waveguide Based Inverse Adiabatic Taper Coupler for Fiber-to-Chip Coupling

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***Abstract*— We present an efficient fiber-to-chip coupling method for polarization independent single mode titanium dioxide-TiO2 waveguide. The proposed inverse adiabatic taper coupler between a lensed fiber and waveguide consists of a spot size converter and allows coupling efficiency of around 85%.**

I. Introduction

Titanium Dioxide (TiO_2) has recently attracted increasing attention for photonic integrated circuits due to its linear and non-linear properties. It has some important advantages that make it compete favourably with silicon, silica and silicon nitride for certain applications. Compared to silicon, TiO_2 is transparent from visible to mid-infrared wavelengths due to its large bandgap ($E_g \geqslant 3.1$ eV) [1]. TiO_2 possesses higher linear refractive index (2.1 - 2.7) [1] than both Si_3N_4 (2.05) and SiO_2 (1.45) resulting in a strong light confinement which allows smaller footprint, hence compact device integration. In addition, the negligible TPA and large enough third order nonlinearity combined with the tight mode confinement makes TiO_2 a promising material for nonlinear integrated optical devices. Furthermore, TiO_2 exhibits a high non-linear refractive index, approximately 3 times larger than that of Si_3N_4 [2]. The reported linear losses of TiO_2 waveguides are generally around 5 dB/cm at telecommunication wavelengths [3].

One of the most important considerations while designing TiO_2 based PIC is its efficient coupling of light from optical fibers to TiO_2 waveguide. Diffraction gratings and edge-couplers are the most popular techniques which are widely used for fiber-to-chip coupling. Diffraction gratings are generally narrow band and require an out-of-plane mechanism to efficiently couple light into waveguides. However, the limitations of this method are complex fabrication steps and large footprint on the chip. On the contrary, edge couplers can produce a high coupling efficiency over a broadband of wavelengths without requiring an out of plane coupling mechanism.

An improved approach of such coupling is the inverse adiabatic taper coupler, where a spot size converter is used to initially couple the light from the fiber into a larger waveguide, and finally couple to desired waveguide following the use of the inversed taper method. This type of coupler is promising because of easier packaging, lower insertion loss and broadband operation. With careful design, it is possible to significantly increase the coupling efficiency and decrease the footprint of the device on chip. Couplers based on inverse taper have demonstrated coupling loss as low as 0.5 - 1.0 dB between sub-micron Si waveguides and fibers with mode field diameters of 2 - 4 µm [5-7]. Specifically, 0.5 dB loss was reported between a fiber with 4.3 µm mode field diameter and a 0.3 × 0.3 µm Si waveguide using a 200 µm long inverse taper [7]. It should be noted that the mode size of the fiber used was several times smaller than that of a standard single mode fiber, which is typical in inverse coupler studies.

II. Design

In this paper, we present design and simulation results of an inverse adiabatic taper coupler consisting of spot-size converter from polymer (BCB) to TiO_2 waveguide. Compared to the grating coupler [4], this inverse adiabatic taper coupler can achieve significantly higher coupling efficiency allowing broader bandwidth with polarization independence. To our knowledge, this is the first reporting of spot-size converter and inverse adiabatic taper coupler based on TiO_2 material.

Fig.1 shows the layout and schematic of the inverse adiabatic taper coupler. Light from the fiber is coupled into a low-index polymer waveguide and transferred into a TiO_2 waveguide with an inverse adiabatic taper. The TiO_2 waveguide is very narrow at the beginning of the taper so that the fundamental mode of the structure is confined not in the TiO_2 waveguide but in the polymer waveguide. As the TiO_2 width increases, the light becomes more and more confined in TiO_2 core. In our coupler, the material of the low-index waveguide was bisbenzocyclobutene (BCB), sold under the name cyclotenetm.

The refractive index of TiO_2 and BCB used in our simulation are 2.12 and 1.53 respectively for the wavelength 1.55µm. The cross-section of BCB was optimized to be 2×2µm. This not only allows efficient optical mode exchange with TiO_2 waveguides but also ensures optimum mode overlap with a lensed fiber of 2.1µm mode field diameter. The mode size of the lensed fiber used in this design is typical of inverse coupler studies. In this device, the TiO_2 waveguide is tapered from 0.05 µm to 0.8 µm within the length of 65µm, where the tapered section is buried in the BCB waveguide.

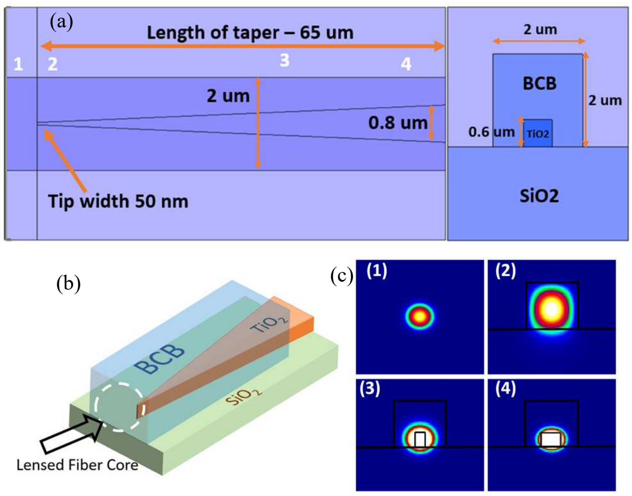

Fig. 1: (a) top view and cross section of the spot size converter with the tapered TiO_2 waveguide buried in BCB waveguide, (b) layout of the inverse adiabatic taper coupler, and (c) mode evaluation of the inverse taper

III. Simulation Results

Multiple simulations were performed with eigenmode expansion method using Fimmwave/Fimmprop software to optimize the device and analyze performance. The simulation results are presented in the figures, where TE0 and TM0 denote as output TE fundamental mode and output TM fundamental mode, respectively. No higher order output modes are excited for the proposed configuration.

The designed coupler supports both fundamental TE and TM modes, where the fiber-to-chip coupling efficiency is around 80% to 85% for wavelengths ranging from 1.3 µm to 1.625 µm. It demonstrates the broadband characteristic of our proposed inverse adiabatic taper coupler.

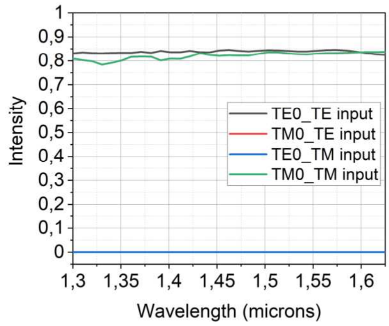

Fig. 2: Fiber-to-chip coupling efficiency in terms of wavelengths for the proposed designed parameters

The simulation results show that the designed coupler allows sufficient fabrication tolerance for both TE and TM mode in terms of the length of the taper and width of the taper tip. Taper length of 40 µm or above will allow more than 80% fiber-to-chip coupling efficiency or less than 1 dB coupling loss, which gives the proposed model more than ±25 µm fabrication tolerance in terms of length. The taper tip-width of up to 0.1 µm will allow more than 80% coupling efficiency or less than 1 dB coupling loss, which gives the proposed model ±50 nm fabrication tolerance in terms of tip width.

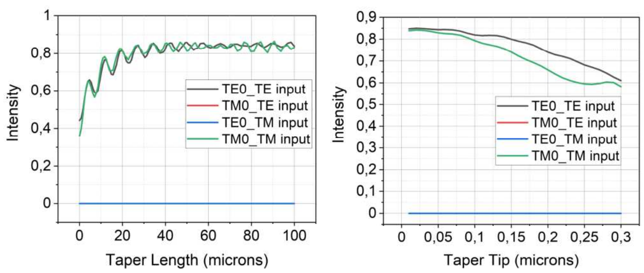

Fig. 3: Fiber-to-chip coupling efficiency in terms of taper length and taper tip variation from the proposed designed parameters

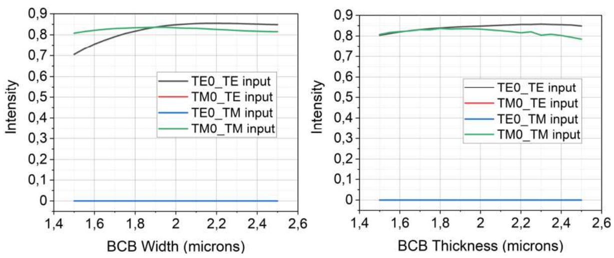

Fig. 4: Fiber-to-chip coupling efficiency in terms of BCB waveguide width and thickness

In terms of the BCB waveguide width and thickness, simulation results present a wide range of fabrication tolerance for both TE and TM mode. BCB width of 1.75 µm or higher allows more than 80% fiber-to-chip coupling efficiency or less than 1 dB coupling loss for both of the modes, which gives the proposed model more than ±250 nm fabrication tolerance in terms of BCB width. In case of BCB thickness, the coupler shows less than 1 dB coupling loss with the range of ±500 nm fabrication tolerance.

IV. Conclusion

We have modelled a compact TiO_2 waveguide based inverse adiabatic taper coupler, and simulated the performance and fabrication tolerance of the device. The coupler possess a strong potential of fiber-to-chip coupling efficiency of more than 80% for both fundamental TE and TM mode. The performance analysis of the device represents its broadband characteristics covering a wide range of wavelengths from O-band to L-band. In addition, the simulation results show wide range of fabrication tolerance, which indicates the possibility of modelling coupler with other specific requirements which can still meet significant fiber-to-chip coupling efficiency. Currently, fabrication work is going on to realize broadband PICs with TiO_2.

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