Demonstration of the first monolithically integrated self-rolled-up tube based vertical photonic coupler

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Abstract: We demonstrated the first monolithically integrated self-rolled-up SiN_x tube based vertical photonic coupler on top of a planar ridge waveguide. The coupling efficiency between the elements is >10 times higher than similar non-integrated device.

OCIS codes: (130.0130) Integrated optics; (130.3120) Integrated optics devices; (130.5990) Semiconductors; (230.4555) Coupled resonators

1. Introduction

Three dimensional (3D) heterogeneous photonic integration is a new route to overcome the material limitation and to achieve enhance functionalities and great flexibility in photonic integrated circuit (PIC) system design. A resonator based vertical photonic coupler is preferred to the most widely used vertically stacked directional coupler (VSDC) because of the higher Q-factor that the resonator coupler may achieve. The self-rolled-up semiconductor tube is a good candidate for this application because it can be fabricated using planar processing techniques and functions as a 3D structure after self-assembly[1]. The self-rolled-up tube had been used to successfully couple light between waveguides [2, 3]. But to monolithically integrate a vertical tube coupler and a planar waveguide has been an unsolved technical challenge. We took up this challenge and successfully demonstrated the first monolithic integration of this vertical photonic coupler with a planar waveguide and observed greatly enhanced coupling between them using the silicon nitride photonics platform.

2. Device Fabrication and Structures

The testing devices were fabricated on a (100) p-type silicon substrate, which contains a 6μm thermal SiO_2 and a 150nm Si_3N_4 formed by low-pressure chemical vapor deposition (LPCVD). The ridge waveguides were formed by electron beam (E-beam) lithography and reactive ion etching (RIE). All the fabricated waveguides have a uniform height of 150nm and their widths vary from 2.0μm – 5.0μm. To facilitate tube formation, we planarized the sample surface by covering the ridge waveguides with a layer of spin-on glass (SOG) thicker than the height of the ridge waveguides, then the SOG was etched back by RIE leaving about 100nm residual to top of the waveguides. The thickness of SOG residual layer is controllable and contributes to the overall coupling distance between tube coupler and ridge waveguides. After planarization, a 20nm sacrificial layer, germanium (Ge), is deposited by E-beam evaporation, and the 2D tube patterns are defined by traditional optical lithography and RIE down to the SOG. Subsequently, a 60nm strained SiN_x bilayer was deposited by dual-frequency plasma enhanced chemical vapor deposition (PECVD) to cover the entire sample, which is composed of a 30nm 380K low frequency (LF) SiN_x and a 30nm 13.56MHz high frequency (HF) SiN_x. The residual stress of LF and HF SiN_x thin film are -900MPa and +300MPa, respectively. A window down to the Ge layer was opened by optical lithography and RIE from one side of the tube pattern to facilitate the tube formation directionality. Once Ge is removed by the etchant (H_2O_2) from this window, the SiN_x lifts up from the substrate, dynamic coherent tearing occurs at two sides and the multi-turn spiral tubular SiN_x structure is formed. What we should emphasize here is that all these fabrication steps are fully compatible with the standard planar silicon processing techniques. The fabricated devices are shown in Fig. 1 below.

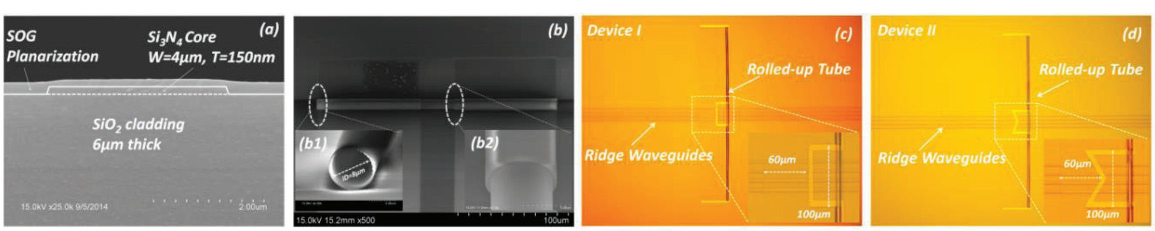

Fig. 1 SEM and optical images of the monolithic integrated tube resonator with ridge waveguide. (a) Si_3N_4 ridge waveguide after planarization by SOG, (b) the self-rolled-up tube resonator, the insets (b1) shows the enlarged cross-sectional view of the tube at one end, (b2) shows the top view of the connection section between the center tube waveguide and the supporting pedals. (c, d) microscopy images of the top view of self-rolled-up tube integrated with planar waveguides. Devices I and II contain different axial patterns in the coupling section.

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3. Device Characterization and Discussion

A standard method to investigate the coupling efficiency between the monolithic integrated tube coupler with planar ridge waveguide is to check the transmission spectrum of the waveguide. The experimental setup is shown in Fig. 2(a). The light source being used is a Hewlett Packard 8168C tunable laser source, which has an output wavelength range from 1470nm to 1580nm. The laser output passes through an optical isolator, a polarization controller and a polarizer to ensure the input light is linearly polarized. Unlike the planar ring resonator that typically uses TM polarized light, the vertical tube coupler is more efficient using TE polarized light. A beam splitter is used to get a small fraction of the input light for reference, the remaining light is coupled into and collected from the ridge waveguide using tapered fiber lens. The transmitted light passes through an optical coupler and is sent to a photo-detector (PD) and a power meter. The reflected light was measured using an optical circulator and another PD.

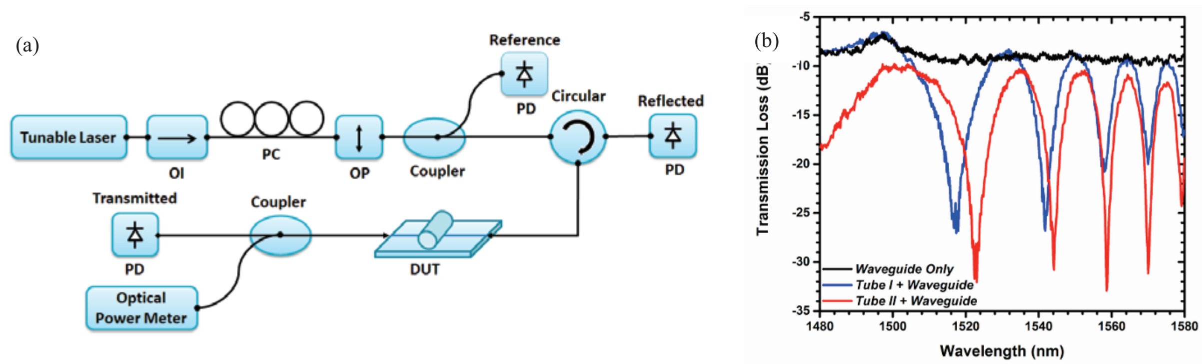

Fig. 2(a) Schematic of the experimental setup. OI: optical isolator, PC: polarization controller, OP: optical polarizer, PD: photodetector, and DUT: device under test. (b) Transmission spectra of the waveguide only (black), the device I (blue) and the device II (red). In all three cases, the waveguides have the same width (4μm) and height (150nm). Device I and II are those shown in Fig. 1(c) and (d), respectively. The only difference between these devices is the axial pattern, i.e. axial confinement, of the coupling section.

Fig. 2(b) shows the experimentally measured transmission spectra for the ridge waveguide and the waveguide coupled with the vertical tube coupler. The blue and the red curves illustrate the transmission spectra of device I and II shown in Fig. 1(c) and (d), respectively. The black curve is the transmission spectrum of a stand-alone ridge waveguide without the vertical tube coupler above it, which was fabricated on the same substrate at the same time, shown as a benchmark. The ridge waveguides in all three cases have the same width (4μm) and height (150nm). Resonant coupling between the planar waveguide and the tube coupler can be clearly identified at discrete wavelengths. The highest extinction ratio is found to be about -23dB at 1558nm for device II, which is an order of magnitude higher than those observed in non-integrated tube to waveguide coupling experiments [2, 3]. The spectral locations of the resonant peaks are slightly shifted between device I and II; this can be explained by the different axial confinement the light experiences when it is coupled into the tube coupler.

4. Conclusion

In this abstract, we presented the first experimental demonstration of a monolithically integrated vertical photonic coupler based on SiN_x self-rolled-up tubes with a planar Si_3N_4 ridge waveguide. The fabrication process is fully compatible with standard and prevailing planar silicon processing technology. Strong light coupling between the ridge waveguide and the vertical coupler was observed. The coupling efficiency is an order of magnitude higher than non-integrated tube and waveguide coupling. This novel vertical coupler opens a new avenue to achieve monolithic 3D photonic integration.

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