PhoxTroT

Photonics for High-Performance, Low-Cost & Low-Energy Data Centers, High Performance Computing Systems: Terabit/s Optical Interconnect Technologies for On-Board, Board-to-Board, Rack-to-Rack Data Links

Collaborative Project
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Report on fabrication and characterization of silicon photonic waveguide platform and passives

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Abstract:

The development of fabrication processes for passive silicon devices is described in this deliverable. Responsible for manufacturing of the devices are UNIVERSITAT POLITECNICA DE VALENCIA (UPVLC) and AMO GmbH (AMO). The technology of both partners based on electron beam lithography for definition of the silicon strcutures.

Keywords: silicon waveguide, linear losses, passive devices

Project Information

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1 Executive Summary

The objective of deliverable D5.2 is the demonstration of the successful development of suitable fabrication process flows for passive silicon devices, like waveguides, couplers, mach zehnder.structures. UNIVERSITAT POLITECNICA DE VALENCIA (UPVLC) and AMO GmbH (AMO) developed independent from each other the necessary process modules. Both partners used electron beam lithography for definition of the structures. UPVLC works with a 30 keV system (Raith 150) and AMO used a100keV lithography tool (Vistec EBPG 5200). Optical characterization of the devices has been achieved.

Within WP5 AMO focuses its activities on reduction of linear transmission losses in silicon waveguides. An optimized EBL process based on multi pass exposure technique has been developed. With this technique transmission losses can be reduces by 1.5dB/cm in single mode silicon waveguides. For a silicon organic hybrid modulator and for the hybrid InP on SOI laser source the manufacturing process of the silicon layer has been optimized

UPVLC developed an EBL process based HSQ as negative tone resist and reactive ion etching with fluoride gases. With this process different passive silicon devices like ring resonators, MZI and photonic crystal membranes have been successfully fabricated. The design of the devices has also been made by UPLVC.

The propagation losses including bending losses of silicon waveguides have been determined. Low loss and low crosstalk tapered waveguide crossing have been investigated. 2x2 Mach-Zehnder interferometer and symmetric add-drop ring resonators have been optically characterized. The spectral output of standard grating couplers has been analyzed.

1.1 Document structure

1.2 Audience

This document is internal to PhoxTroT project consortium.

2 Fabrication process for passive photonic structures

2.1 AMO: EBL based fabrication

2.1.1 Linear losses measured in single mode waveguides

The most basic and elementary elements of silicon photonic devices and circuits are waveguides. Linear transmission losses are the key figure-of-merit to assess and benchmark the quality of the waveguide fabrication. Within the PhoxTroT project AMO continuously works on optimization of the fabrication processes and searches for new ways to decrease linear transmission losses. The fabrication processes of AMO rely on electron beam lithography (EBL) and reactive ion etching (RIE) processes. The EBL processes are based on the use of hydrogen silsesquioxane (HSQ) as a negative tone resist material. A Vistec EBPG 5200 EBL system operates at 100kV acceleration voltage. An optimized high contrast development process is necessary to achieve high resolution, a step resist profile and a smooth resist surface. Dry etching is carried out using an Oxford Plasmalab 100 ICP-RIE tool. An optimized etching process based on HBr chemistry is used for waveguide and device fabrication. All waveguide test structures and device designs within PhoxTrot are realized on silicon-on-insulator (SOI) material with a top silicon thickness of 220 nm and a 3 µm buried oxide layer.

The waveguide structure to analyze the influence of different exposure strategies is a single-mode slab waveguide with the geometry depicted in Figure 1.

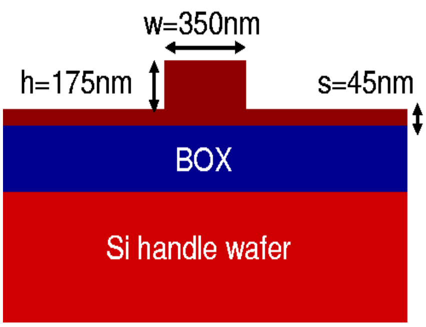

Figure 1: Schematic of waveguide cross section. Waveguide width w=350nm, height h=175nm and slab height s=45nm.

Propagation losses are measured at □□=1.31 □m by the cutback method, which is based on a comparison of transmission through waveguides of different length. Figure 2 depicts a typical cutback layout.

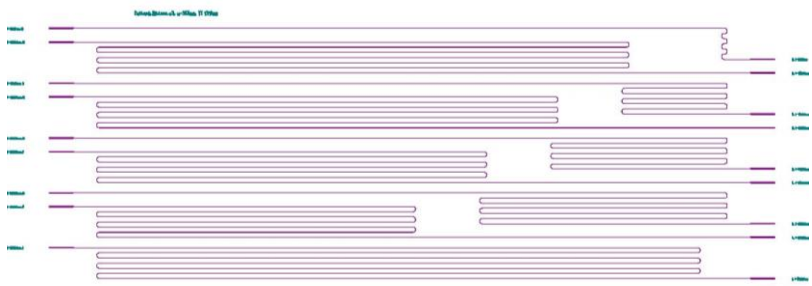

Figure 2: Cutback Design (Design AMO)

The cutback method is applied to measure the transmission for waveguides with 9 different lengths and to calculate the resulting linear losses in the silicon waveguides. Measurements were carried out by a standard continuous wave measurement setup. Grating couplers have been used to connect the waveguides with the measurement setup via optical fibers. Special care has been taken in both design and fabrication of the coupling structures to achieve homogeneous and stable coupling conditions for all waveguides as measurement accuracy crucially depends on a good critical dimension control regarding the grating couplers.

The influence of the exposure strategy on linear transmission losses in silicon waveguides fabricated by electron beam lithography has been investigated. Three different exposure strategies (conventional single pass exposure, double pass exposure and a multi exposure with four passes are compared regarding their respective losses in slab waveguides. In Figure 3 the transmission losses for each of the three exposure strategies are plotted as a function of the number of exposure passes. For a conventional single pass exposure, losses of 4.0 dB/cm have been measured. For the double exposure and the multi exposure with four passes the optical propagation losses dropped to 3.4 and 2.4 dB/cm, respectively.

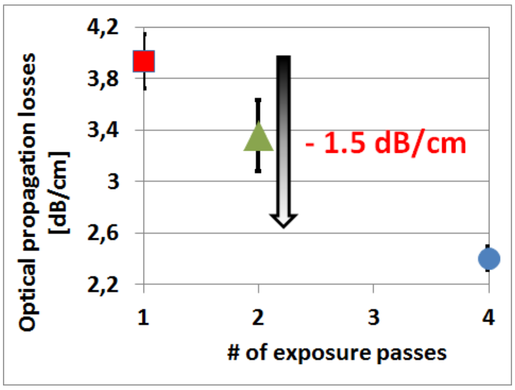

Figure 3: Optical propagation losses for different exposure strategies: single pass (red square), double pass (green triangle) and four pass exposure (blue disc).

A multi pass exposure technique can obviously reduce the OPLs in single mode silicon waveguides by at least 1.5 dB/cm without any further refined post processing steps. At the same time the measurement accuracy increases with increasing number of exposure passes as can be seen from the error bars also plotted in Figure 3. Both effects can clearly be attributed to the benefits of the multi pass exposure approach: i) reduction of write field and sub field stitching errors; ii) reduction of the influence of shot noise; iii) reduction of roughness introduced by the discrete step size of the electron beam.

Similar experiments have also been made for strip silicon waveguide. In contrast to slab waveguides, described above, the top silicon layer beside the waveguide is completely etched away down to the BOX. These waveguides are used within PhoxTrot for the realization of silicon organic hybrid modulator (SOH-Modulator). Optical propagation losses are in the range of 2 dB/cm for single mode strip waveguides

2.1.2 Passive photonic devices for WP4/WP5 and WP6

KIT and AMO worked on fabrication and characterization of suitable passive test structures for silicon organic hybrid modulator (SOH-Modulator), realized in Task 4.3 of the PhoxTrot project.

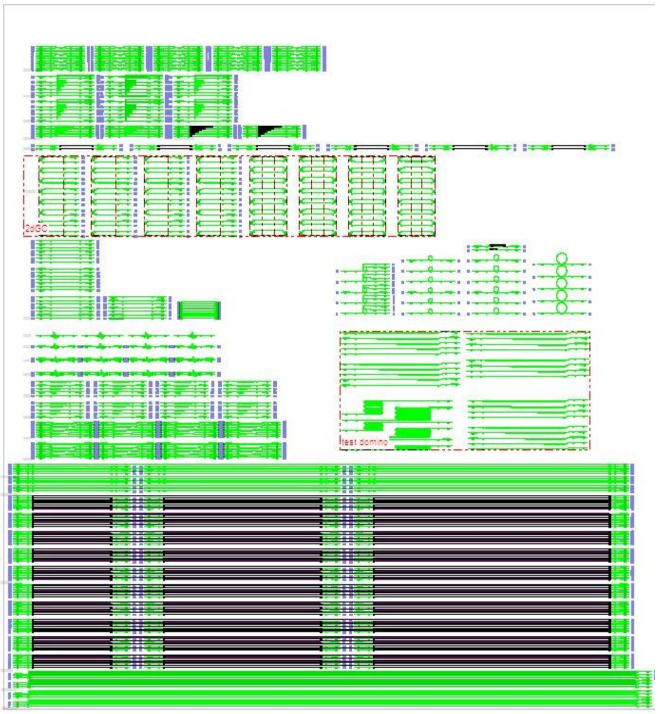

Figure 4: Passive test structures SOH modulator (Design KIT).

A chip layout based on simulations and previous experiments has been designed by KIT. The overview of the design is shown in Figure 4. It contains the following key elements towards the realization of IQ modulators:

Slot waveguides and strip-loaded slot waveguides: The optical losses for different variations of the slot and rib width have been investigated. The waveguide dimensions have a crucial influence on the excess loss as well as on the electro-optic parameters of the modulator like the modulation bandwidth. Slot waveguides with an asymmetric slot position are investigated for the possibility to further reduce the losses.

Transition from strip to slot waveguides: The transition has to be optimized towards low back reflection and low loss.

Multimode interference couplers: These couplers serve as basic splitter/combiner in the interferometric modulator setup. Here a parameter variation was done to get the optimal design for the fabrication process with respect to insertions loss and an extinction which ratio are of great importance for the modulator performance. Both 1x2 MMI and 2x2 MMI were investigated.

Passive Mach Zehnder structures: Test Structures for other passives like strip or ridge waveguides and grating coupler for routing were placed on the design to evaluate the combined loss of all passive elements. AMO successfully fabricated the devices and KIT did the optical characterization of the devices

In the SOH approach silicon waveguides are functionalized with an organic cladding material. AMO is responsible for the realization of the silicon platform of SOH modulators. The modulator design is made by KIT, which is also responsible for the deposition of the organic cladding material and for characterization of the final modulator devices. Basic building block is a Mach Zehnder modulator with slotted waveguide.

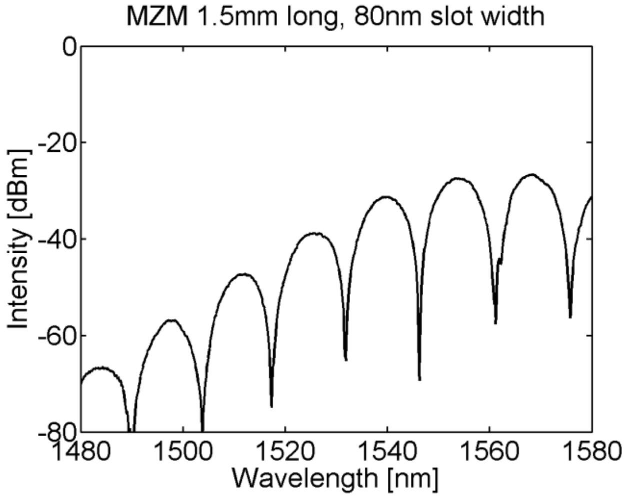

Figure 5: Optical transmission versus wavelength for a Mach Zehnder phase shifter based on slotted waveguides .

To demonstrate the functionality of the Mach Zehnder device based on slotted waveguides, Figure 5 shows exemplary the optical transfer behavior of such a device.

The device layer of the modulator consists of both rib and strip waveguide structures. Figure 6 shows a strip to slot converter to couple access strip waveguides to the phase modulator. Again these structures have manufactured by EBL. In a first lithographic process the waveguides have been defined. An optimized high contrast development process is necessary to achieve high resolution, a step resist profile and a smooth resist surface. The waveguide patterns are etched 150nm deep into the Top silicon layer in an ICP-RIE etching process based on HBr chemistry. For final definition of the gap between the silicon rails again EBL using HSQ has been used. In contrast to the first HSQ layer a significant thicker HSQ layer has been chosen. The first HSQ resist layer was not removed from the wafer after the first etching step, as it acts as the masking layer during the second etching step. After EBL exposure and subsequent development the gap have been defined in thick HSQ layer and the structures have been fully etched down to the buried oxide (BOX) in a second ICP-RIE etching process

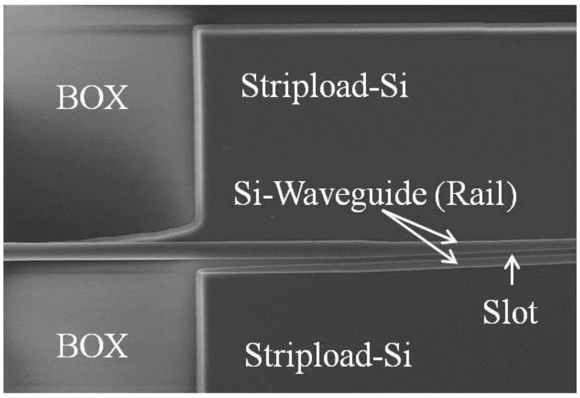

Figure 6: SEM micrograph of a strip to slot converter.

Finally grating couplers used to couple light from a single mode fiber to the silicon chip are fabricated by EBL and subsequent reactive ion etching. The grating coupler have been defined the positive tone ZEP resist, as shown in Figure 7. A fluorine based reactive ion etch process with inductive coupled plasma source were used to etch 70nm deep grating couplers. The process was optimized for high selectivity to ZEP resist and anisotropic etch profile.

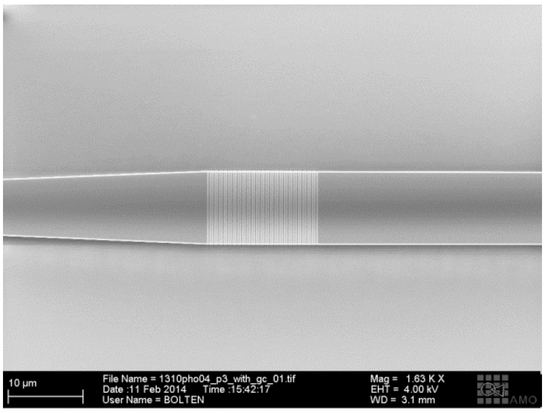

Figure 7: SEM picture of a shallow etched grating coupler.

Towards the realization of electrically powered hybrid InP- on SOI laser sources CNRS designed resonators structures. Main building blocks of the design are micro-cavities embedded in a straight silicon strip waveguide. The diameter of the holes is varied. Devices are realized on SOI substrate by AMO using electron beam lithography (EBL) and reactive ion etching. The devices have been fabricated by AMO. Typical resonator structures are shown in Figure 8.

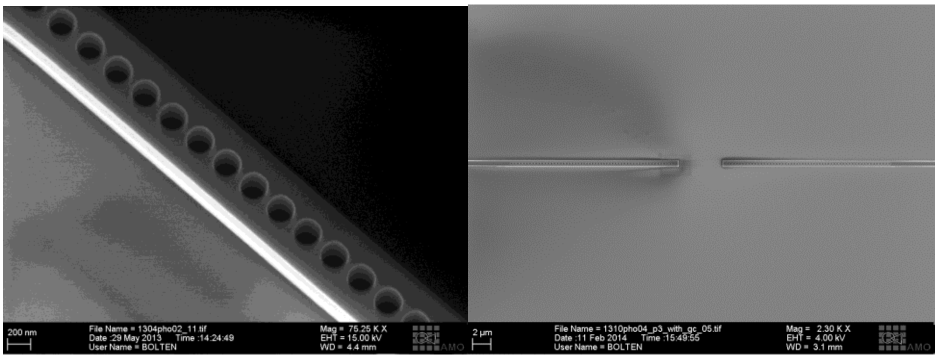

Figure 8: SEM micrograph of micro cavity resonator for hybrid InP on SOI laser.

2.2 Fabrication of photonic devices in NTC-UPVLC Clean room

The Phoxtrot passive samples were fabricated in the NTC-UPVLC clean room. The main specs of the NTC-UPVLC clean room are summarized in the following:

- 250+250 m^2 cleanroom
- Class 10 – 100 –10.000
- Full line of 6" silicon micro-nanofabrication equipment
- Fully equipped physical characterization, optical coupling and packaging labs

Figure 9 shows some images of the clean room including e-beam and mask-aligner systems:

Figure 9: Images of the NTC clean room with e-beam and mask-aligner tools.

2.2.1 NTC-UPVLC: EBL based fabrication

The photonic structures were fabricated on standard silicon-on-insulator (SOI) samples of SOITEC wafers with a top silicon layer thickness of 220 nm (resistivity ρ ~1-10 Ω cm^{-1}, with a lightly p-doping of ~10^{15} cm^{-3}) and a buried oxide layer thickness of 2 μm. The structure fabrication is based on an electron beam direct writing process performed on a coated 100 nm *hydrogen silsesquioxane* (HSQ) resist film. This electron beam exposure, performed with a Raith150 tool, was optimized in order to reach the required dimensions employing an acceleration voltage of 30 KeV and an aperture size of 30 μm. The HSQ is a negative resist which implies that patterns were directly exposed (no trench exposures).

After developing the HSQ resist using TMAH as developer, the resist patterns were transferred into the SOI samples employing an also optimized Inductively Coupled Plasma- Reactive Ion Etching process with fluoride gases (SF_6/C_4F_8). Both gases are injected at the same time under tipical plasma conditions for silicon etching (20 mT pressure, low bias voltage, and a SF_6/C_4F_8 flow ratio of 1.5) which produces anisotropic etching with smooth sidewalls. Furthermore, the etching process was optimised to reach 70 nm deep structures (RIDGE waveguides). Once the silicon is etched, the samples were covered with 1 micron of silicon dioxide deposited by means of PECVD tool (AMI-Centura).

The process flow diagram is described in the following Figure 10:

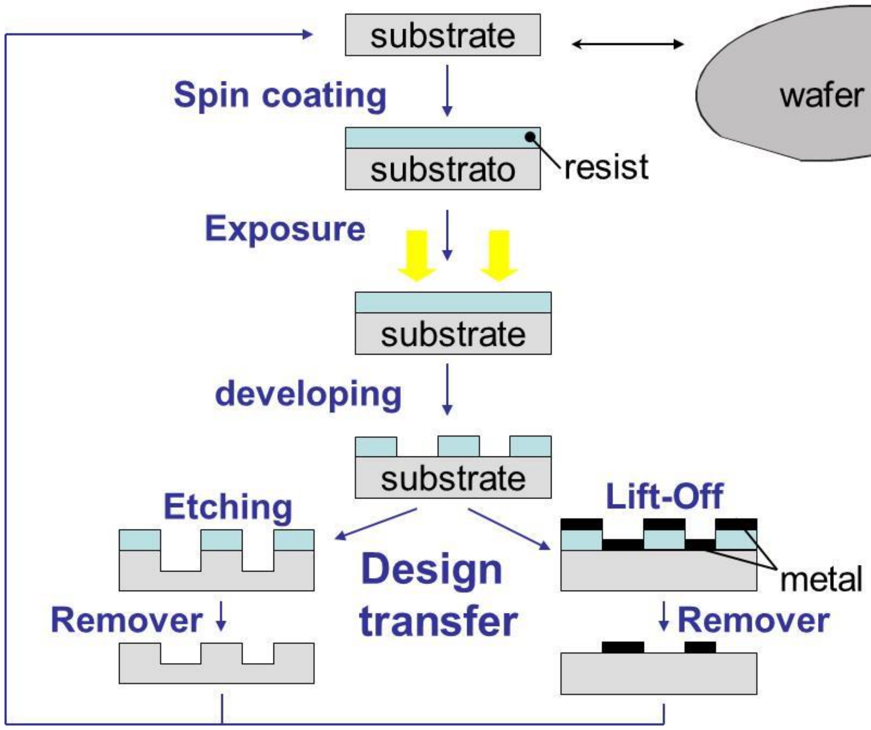

Figure 10: NTC fabrication process.

Figure 11 shows some designs fabricated in the NTC-UPVLC clean-room:

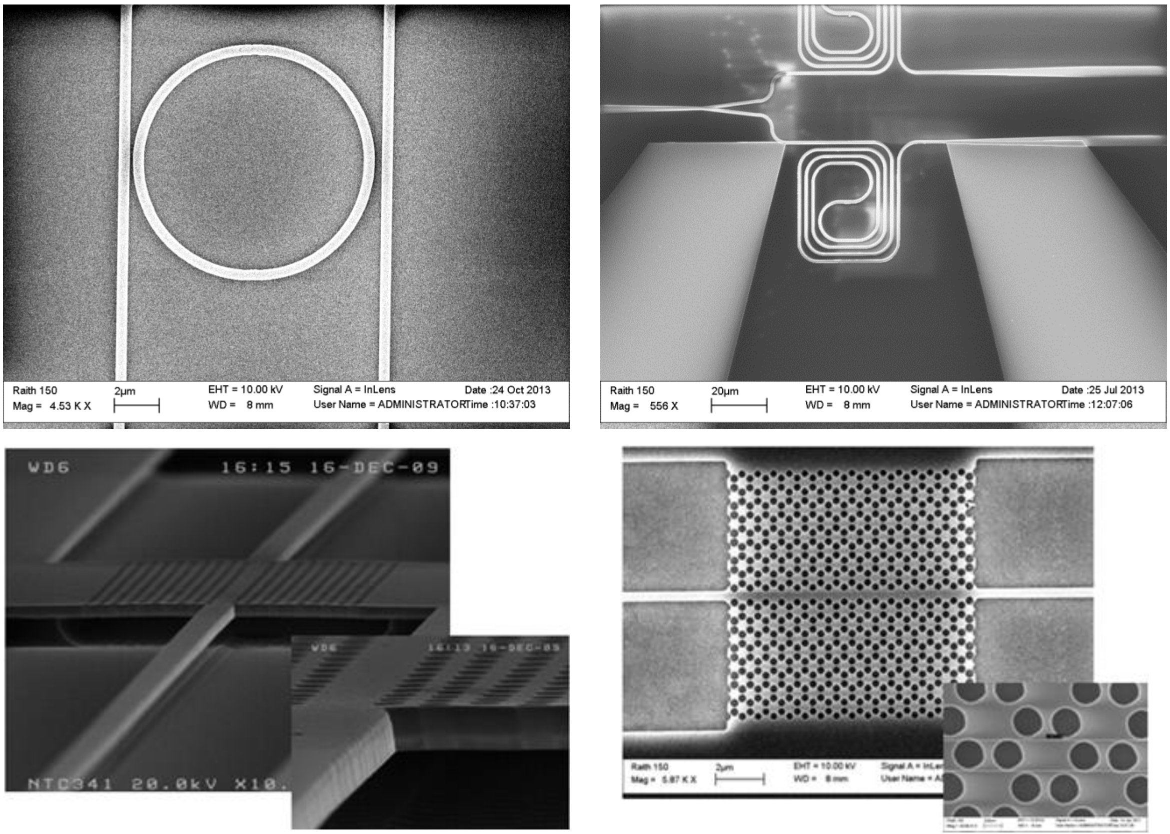

Figure 11: SEM images of NTC-UPVLC fabricated samples. Ring resonators, MZI and photonic crystal membranes.

2.2.2 Characterization of passive components.

Several samples containing key passives structures for Project Phoxtrot were designed and fabricated in NTC-UPVLC clean room. Some of the GDS layouts are shown in below in Figure 12.

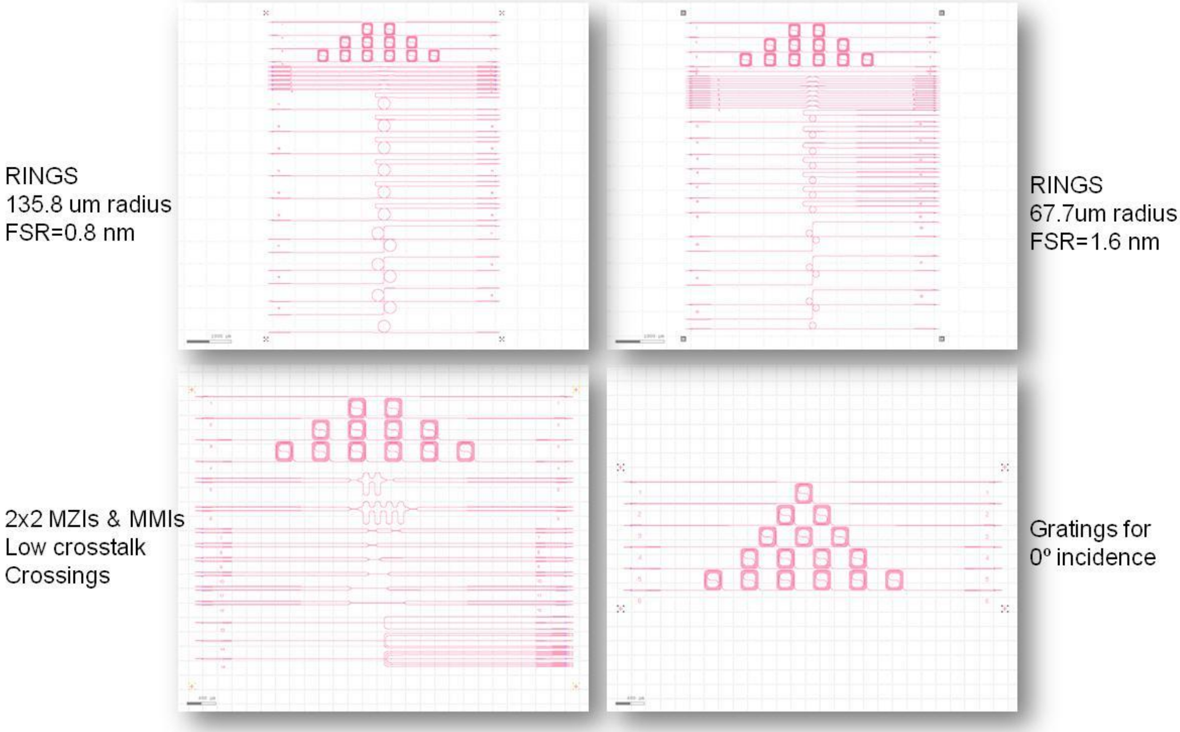

Figure 12: GDS layouts for passive component testing.

a) Rib waveguides and bends

The passive components were all designed relying on a shallow etched waveguide configuration as shown on Figure 13.

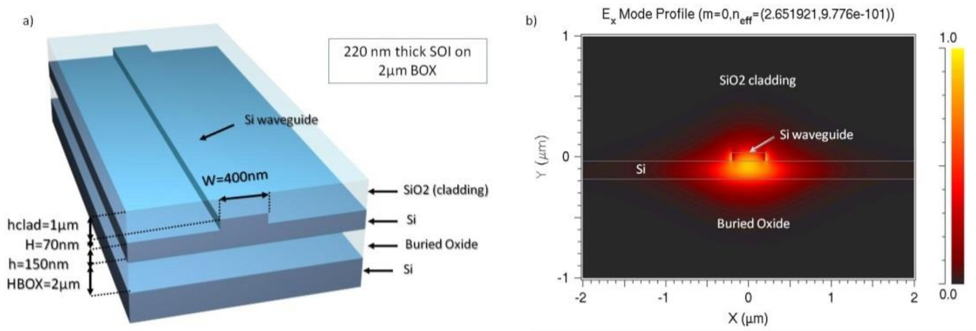

Figure 13: a) Schematics of the shallow etched waveguide configuration. b) TE fundamental optical mode @ 1.55 µm wavelength.

The passive structures were characterized across the 1480-1580nm using a Tunable Laser Diode (TLD) and a chip characterzation probe station, using the experimental setup illustrated in Figure 14 (a). For the estimation of the propagation losses a set of cutback sections were fabricated and characterized, featuring four structures of straight waveguides, and a set of waveguides with two, three and four spirals of the same length respectively, as shown in Figure 14 (b). The first section of the chip features four structures of straight waveguides (WG) (str.1), and a set of two, three and four spirals of the same length, respectively. The length of a single spiral was measured to be 120x6 (right straight vertical WG) + 140x5 (top straight horizontal WG) + 140x6 (left straight vertical WG) + 100x5 (bottom straight horizontal WG) + 5x2πR (Perimeter of bends WG) + 50 (middle horizontal straight WG) = 10331 um. The obtained measurements for the additional insertion losses versus the additional propagation length for the four cubtack measurements are depicted in the graph of Figure 14 (c), where after a linear regression the propagation losses are estimated to be 7.8 dB/cm.

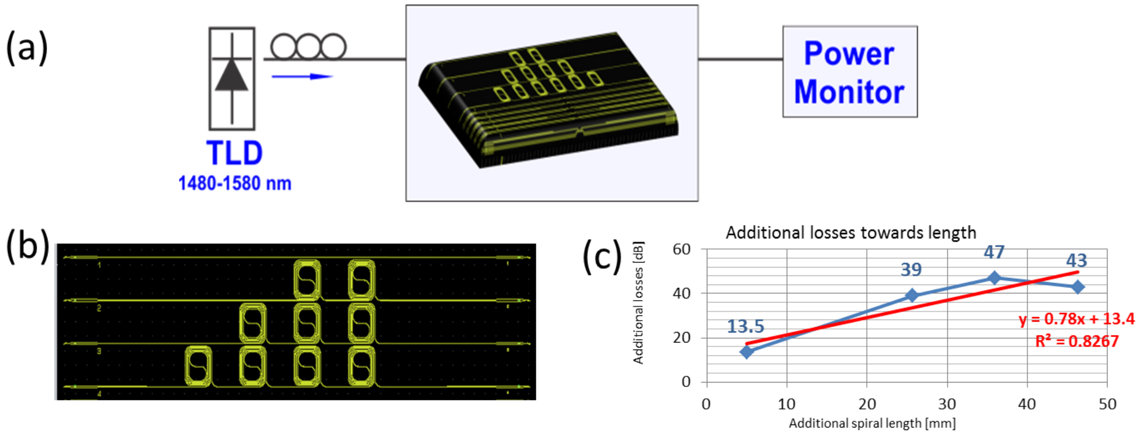

Figure 14: (a) 1st Round of passive structures experimental setup employed (b) Cutback measurements for measuring the propagation losses of rib waveguides and bends (c) Cutback measurement results.

It should be however noticed that the 7.8 dB/cm value includes the bend losses in the successive spiral structures. Therefore, in order to separate the losses dues to the bends and those produced by the straight sections, we performed an estimation of the losses due to curvature. As can be seen on Table 1, for the cut back bend radii of 50 μm were considered. For each of these 90° bend the losses were on average 0.18575 dB/per 90° bend. From these measurements the additional losses produced the bend were included and the losses of the straight section were extracted leading to a loss value of 4.86 dB/cm (see Figure 15).

Radius (μm)	Loss (dB/90° bend)
15	0.7907
30	0.29575
50	0.18575
75	0.01875

Table 1: 90° Bend loss for varying radius of shallow etched rib waveguides.

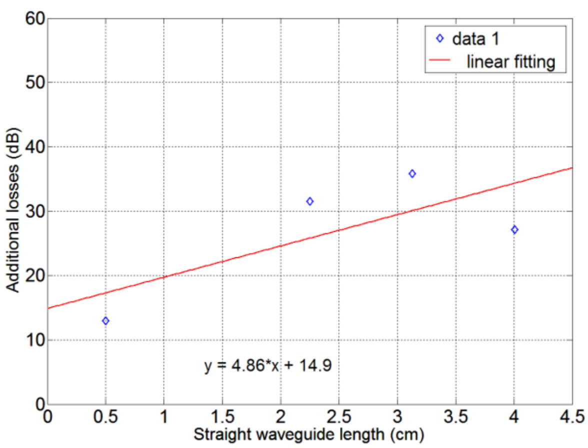

Figure 15: Cutback measurement results giving the propagation losses of straight rib waveguides. Losses are found to be 4.86 dB/cm.

b) Crossings:

Low loss and low crosstalk tapered waveguide crossings were investigated (see Figure 16). The insertion loss per crossing is <1 dB and the crosstalk <-22 dB. A picture of the fabricated waveguide crossing together with characterization measurements are shown below.

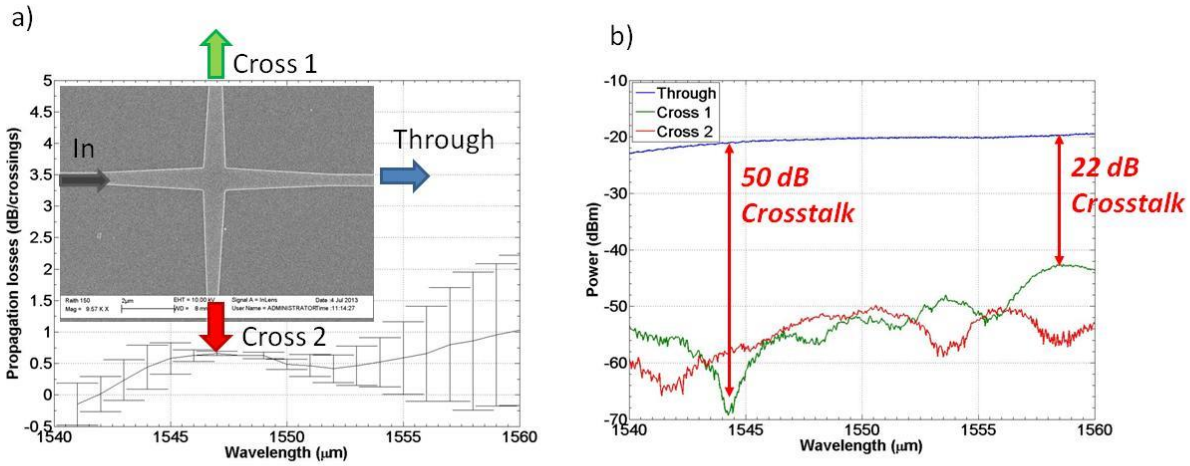

Figure 16: a) Fabricated waveguide crossing and insertion loss vs wavelength. b) Transmission spectra along the different paths.

c) 2x2 Mach-Zehnder interferometers:

The MZI consists of straight and bent waveguides and 2 multimode interference (MMI) couplers. One fundamental aspect of these MMI couplers is that they must provide -3dB splitting ratio (50 % of the input power in each arm). We confirmed this by characterizing two asymmetric MZIs featuring a path length difference of 425 and 850 μm respectively for the 200 GHz (1.6 nm) and 100 GHz (0.8 nm) ITU grid spacing, as shown in Figure 17. The measured free spectral range (FSR) 196 Ghz (1.57 nm) and (0.77 nm) 96 GHz are in good agreement with the theoretical ones. Additionally, as depicted in Figure 17, the crosstalk (extinction ratio) is < -15 dB in the asymmetric cases, confirming the good splitting behavior of the MMI couplers. As a reference, the symmetric MZI shows good extinction ratio <-10 dB and up to <-18dB. Furthermore, the insertion losses of the MMIs were extracted using cascaded MMIs and the cut back method. According to our experimental results shown in Figure 18, a single MMI coupler features on average 0.65 dB insertion loss (min 0.25 dB/MMI max 0.9 dB/MMI), in line with our theoretical calculations, (0.5 dB).

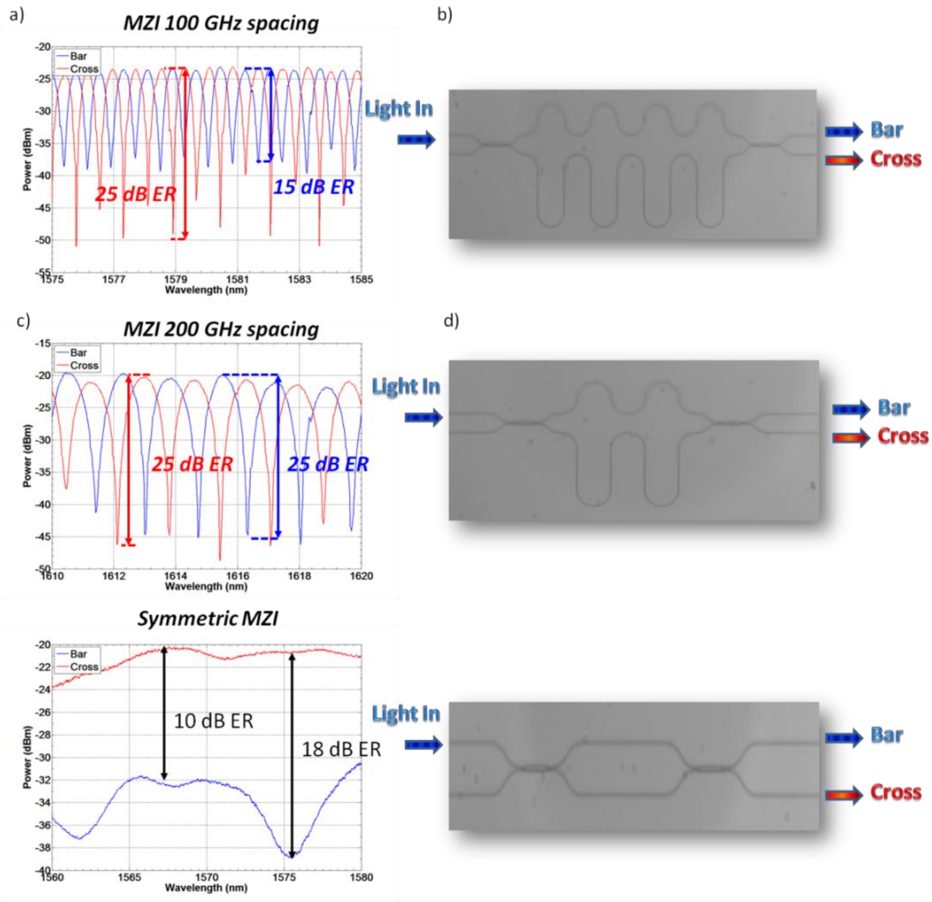

Figure 17: a): Transmission spectrum of MZIs with a)100 GHz (0.8 nm) b) 200 GHz (1.6 nm) ITU grid spacing c) Symmetric MZI 3dB MMI couplers against wavelength.

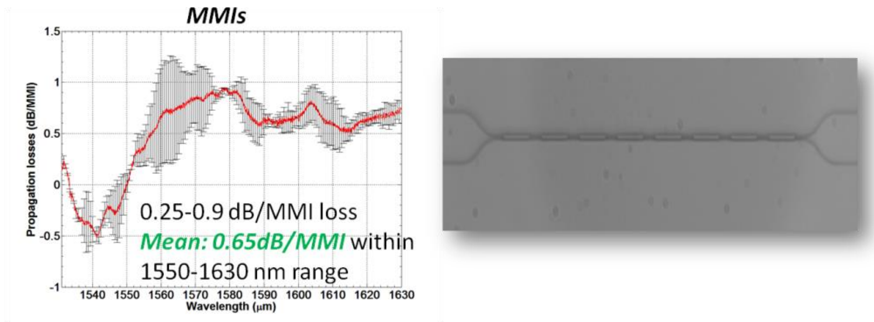

Figure 18: Insertion losses of the 3dB MMI couplers against wavelength.

d) Symmetric Add-drop rings

Additionally, add-drop rings were also fabricated taking into account the experimental values of the coupling coefficients and losses. Some examples of the output spectra are shown in Figure 19.

e) 2x2 X-shaped dual rings

2x2 dual ring resonators and add-drop ring resonators for 100 GHz (R=135.8 µm) and 200 GHz (R=67.7 µm) spacing were also optically characterized. The experimental spectra are shown below. As can be seen in Figure 20 the experimental FSRs (1.55nm and 0.753nm) fits well our theoretical predictions. Additionally, extinction ratio between the through and cross port reaches 30 dB and 15 dB for the small (200 GHz) and large ring (100Ghz), respectively. When the cross port is transmitting and the though port is extinguishing, the extinction ratio is >10dB and >6 dB for the small (200 GHz) and large ring (100Ghz).

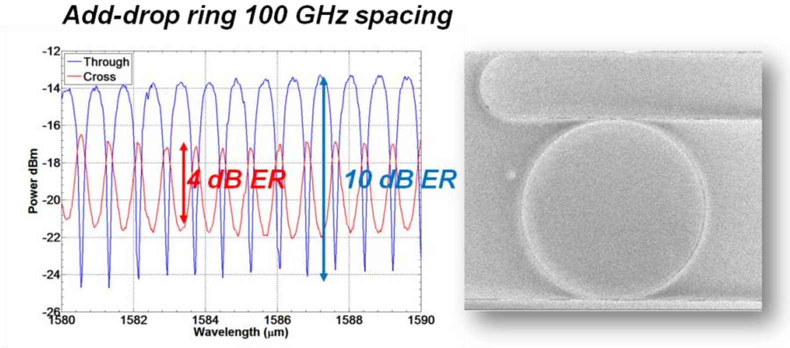

Figure 19: Example of measured output spectra of and add drop ring and a 2x2 X-shaped dual ring

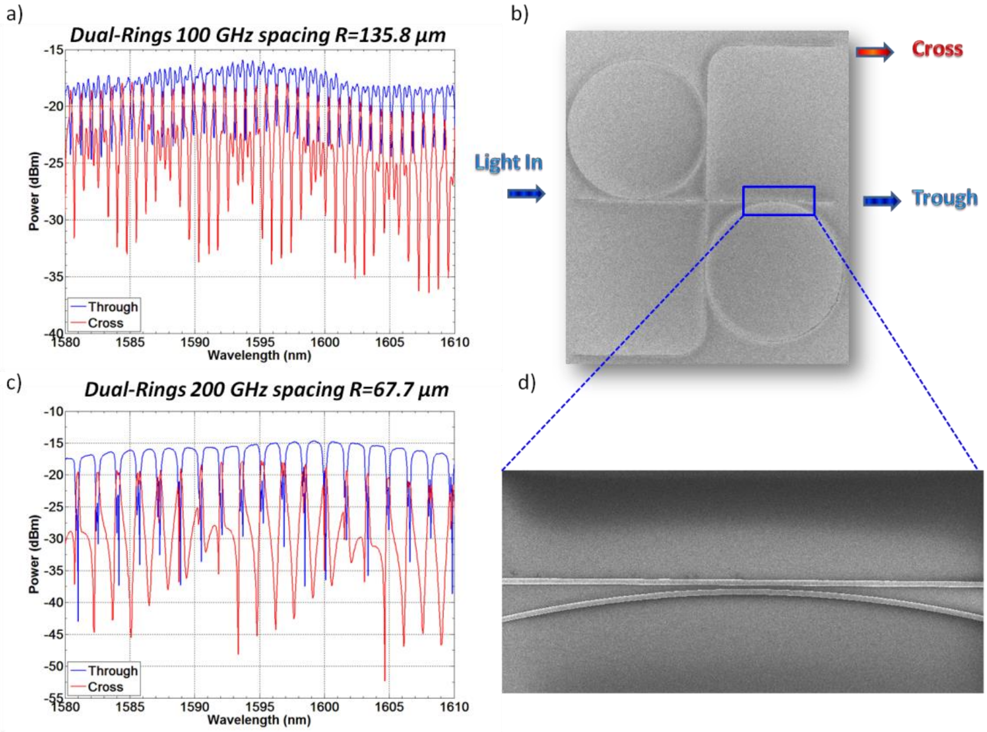

Figure 20: a) Transmission spectrum of a X-shape dual-ring resonator with 100 GHz b) 200 GHz spacing c) SEM picture of the 100 GHz Dual ring resonator d) close up view of the bus-to-ring section.

f) Standard grating couplers

The spectral output of the standard grating couplers employed features a peak around 1590nm, as shown in Figure 21.

In order to shift the peak gain closer to the 1550nm, the grating coupler studied in [1] should be employed: For a tilt angle of 10°, which is sufficient to avoid reflection and an etch depth of 70nm, coupling efficiency to the fiber is approximately 37%, for a grating period of a = 630 nm and a filling factor of 0.5. The red shift in the grating response is due to the shallow 70 nm etch without a second deep-etch step of the large input/output waveguides. Similar grating coupler performance has been achieved by simply reducing the period down to 610 nm in order to blue shift the spectra toward 1550 nm.

[1] D. Taillaert, et. al., "Grating Couplers for Coupling between Optical Fibers and Nanophotonic Waveguides", Jpn. J. Appl. Phys. 45 (2006) pp. 6071-6077

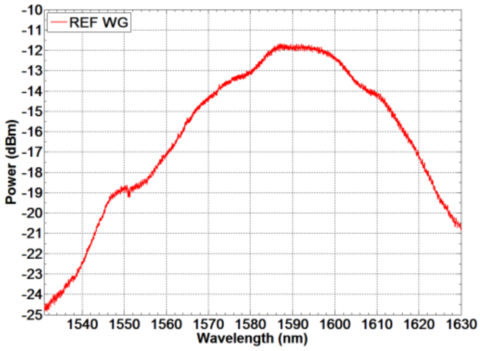

Figure 21: Example of a Fiber-to-fiber spectral response for the standard couplers employed.