APSUNY Process Design Kit (PDKv3.0): O, C and L Band Silicon Photonics Component Libraries on 300mm Wafers

Erman Timurdogan, Zhan Su, Ren-Jye Shiue, Christopher V. Poulton, Matthew J. Byrd, Simon Xin and Michael R. Watts
Analog Photonics, 1 Marina Park Drive Suite 205, Boston, MA, 02210
erman@analogphotonics.com

Abstract: An updated process design kit (APSUNY PDKv3.0) is introduced with verified passive and active O+C+L band silicon photonics component libraries, which includes 50Gbaud (100Gbps) capable modulators, high yield splitters and detectors on 300mm SOI wafers.

OCIS codes: (130.3120) Integrated optics devices; (250.3140) Integrated optoelectronic circuits; (130.1750) Components.

1. Introduction

Silicon photonics enables large-scale integration of photonic integrated circuits (PIC) by utilizing a fabrication platform that produces compact, low-power and low-cost devices in high volumes. Large-scale integration is possible if there are consistent high-performance silicon photonic components and building blocks within a fabrication process that can be modelled at a system scale and laid out in a hierarchical design methodology. Initially, individual companies formed their own design teams to develop these building blocks on private silicon photonic platforms. Recently, "fabless" public platforms have been made accessible through multi-project wafer (MPW) runs and process design kits (PDKs), similar to CMOS electronics design flows [1-3]. These platforms, along with the integration of Electronic-Photonic-Design-Automation (EPDA) flows, lower the barrier to entry for both industrial and academic entities and allow non-experts to design with known fabrication processes and photonic components. Moreover, separation of component and process development from the system architecture allows these entities to reduce risk of device failure and time to market. Analog Photonics (AP) provides such PDKs on the SUNY Polytechnic Institute platform with schematics, layouts and models in major EPDA tools on AIM Photonics MPW runs [2]. AP has released major updates to the component libraries semi-annually since 2016 with increasing and verified performance. This process uses 300mm silicon-on-insulator (SOI) wafers with one silicon and two silicon nitride layers (First and Second SiN: FN, SN) for optical manipulation and waveguiding, one germanium layer for detection, two metal levels for electrical routing and a trench for sensor applications. In early 2018, PDKv2.0 was released with a comprehensive set of active and passive PDK component libraries that support couplers, waveguides, power taps, splitters, analog and digital modulators and detectors over the C and L band [3]. Although PDKv2.0 met the requirements of telecommunications (i.e. coherent optics), radio-frequency or analog transceivers, and sensors applications, it lacked the O band support needed for high performance computing and datacenter interconnects that are governed by the IEEE 802.3bs standard and multi-source agreements (MSAs).

Here, we present the highlights of the APSUNY PDKv3.0 release. With this release, AP extends the PDK component libraries with O band support and demonstrates maturity in process, design and characterization methods of C and L band photonic components. O band components include waveguides, couplers, splitters, modulators and detectors. Using these components, a communication link that operates up to 32Gb/s is demonstrated with on-chip modulators and photodetectors at λ~1310nm with a low CMOS-compatible drive voltage of 0.75Vpp. Wafer-scale measurements of the C and L band microdisk modulator resonant wavelength distribution are shown with a small standard deviation of $\sigma_{\Delta\lambda}$=2.14nm which can be corrected with the included heater to maximize yield. C and L band Mach-Zehnder modulator (MZM) is also updated to support 50Gbaud (100Gb/s) PAM4 signaling with 2Vpp differential drive. C band detector responsivities were measured to be repeatable across six runs and dies from four quadrants of a wafer with standard deviations of $\sigma_{responsivity}$=2.7% and 1.2%, respectively. Finally, the C and L band 1-by-2 splitter was measured with a low-loss (<0.16dB) and split ratio variation of σ<0.6% (50.6/49.4 split ratio) across multiple dies which is crucial for MZMs with high extinction ratios and balanced detection with high common mode rejection ratios.

2. O Band Active and Passive PDK Component Library

The O band PDK component library provides essential active and passive devices which are depicted in an example photonic integrated circuit (PIC) in Figure 1-a. The passive component library includes waveguides, edge couplers, layer transitions (escalators) and splitters. Both silicon (Si) and silicon nitride waveguides (FN, SN and FNSN) can be used for optical O band routing which offer unique advantages within this PDK (Figure 1-b). The Si strip and low-loss Si waveguides were measured to have less than 2dB/cm and 1dB/cm loss, respectively (Figure 1-c). These Si waveguides can be used for high confinement and tight bend radii optical routing. When the confinement and bend radii are not constrained, waveguides with both nitride layers (FNSN waveguide) can be used which have a

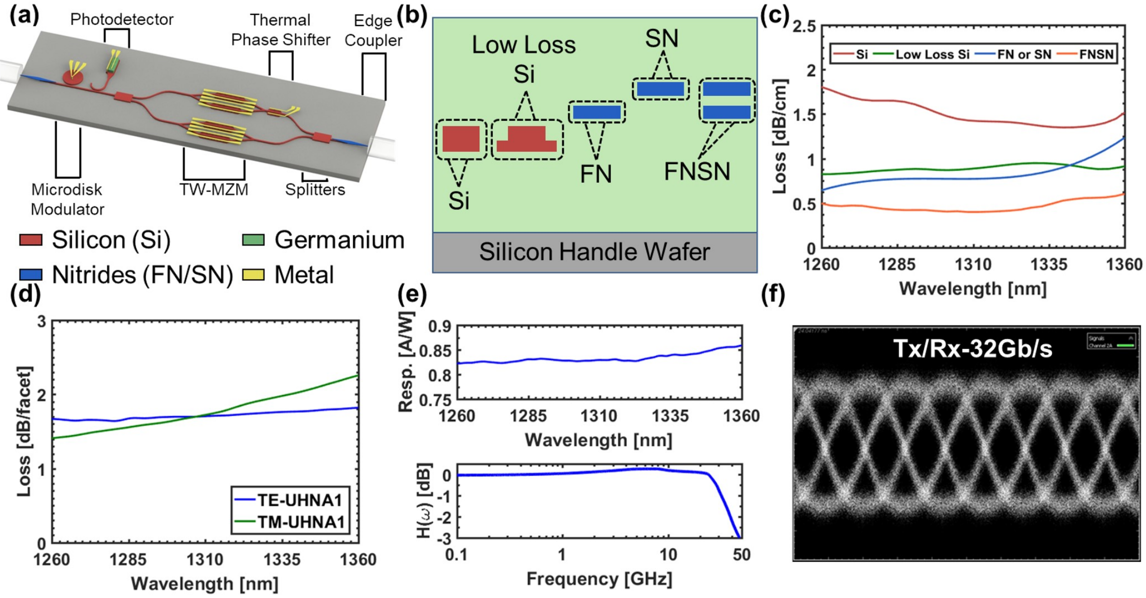

Figure 1. (a) 3D sketch of O band component library in an example PIC. (b-c) Waveguide types and propagation losses of O band waveguides. (d) UHNA1 single mode fiber to edge coupler coupling efficiency. (e) O band photodetector responsivity (top) and electro-optic response (bottom). (f) Eye diagram of a communication link at 32Gb/s that is formed by O band PDK microdisk modulator and detector at λ~1310nm.

loss of less than 0.5dB/cm across the O band (Figure 1-c). The Si and silicon nitrides were also used in a low-loss fiber-to-chip edge coupler, resulting in an average loss of 1.7dB/facet and a low polarization dependent loss (PDL) of ±0.5dB across the O band. The mode field diameter of the coupler was designed to be 4.8um for both polarizations (TE, TM), matching well with commercial off the shelf (COTS) ultra-high numerical aperture (UHNA1) single mode fiber.

The active component library includes a thermal phase shifter, modulators, and detectors (Figure 1-a). The O band photodetector uses a vertical p-i-n junction within the germanium layer for photocurrent generation. At -1V bias, the detector was characterized to have a 0.84±0.02A/W responsivity across the O band and >40GHz optical-electrical bandwidth (Figure 1-e). The microdisk modulator has an p-n junction for rapid electro-optical modulation that is capable of transmitting up to 32Gb/s non-return-to-zero (NRZ) data with a >3.5dB dynamic extinction ratio and <3.1dB insertion loss using only a $0.75V_{pp}$ AC coupled drive. As a demonstration, a communication link was formed by coupling the modulator chip to the photodetector chip through a single mode fiber. The modulator was contacted with a GSG probe and a 32Gb/s data stream was applied. Then, the detector was contacted with a terminated GSG probe and a bias-tee is used to apply -1V to the detector. The received signal out of the detector was recorded by a digital communication analyzer, showing an open received eye diagram (Figure 1-f). This end-to-end link demonstration shows the ability of the PDK components to form commercially viable prototypes and systems.

3. C and L Band PDK Component Library Maturity and Characterization

We highlight the robust passive performance by measuring the C and L band silicon microdisk modulator resonant wavelength distribution within a 300mm wafer (Figure 2-a). The resonance wavelength across the wafer is tightly grouped together and the variation across the wafer was extracted to be $\sigma_{\Delta\lambda}$=2.14nm, corresponding to an

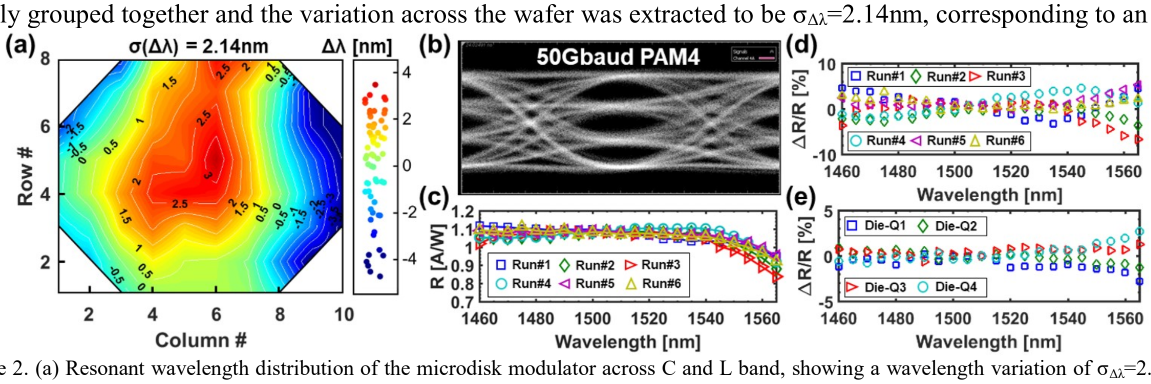

Figure 2. (a) Resonant wavelength distribution of the microdisk modulator across C and L band, showing a wavelength variation of $\sigma_{\Delta\lambda}$=2.14nm across the 300mm wafer. (b) 50Gbaud PAM4 eye diagram of C and L band MZM. (c) Responsivities of photodetectors fabricated in multiple MPW runs of AIM Photonics. (d) Responsivity variations over 6 MPW runs/wafers of the photodetectors. (d) Responsivity variations of photodetectors on the Run#5 wafer.

effective index change of $\Delta n_{eff}=5\times10^{-3}$ or $\Delta n_{eff}/n_{eff}$ ~0.2%. The measured wavelength variations can be efficiently compensated with the integrated thermal tuner in the PDK component which has an efficiency of 0.54nm/mW (14.8μW/GHz). The highlight for active performance is the C and L band MZM that operates up to 50Gbaud (100Gbps) PAM4 modulation format with 2Vpp differential drive and >4dB extinction ratio at quadrature (Figure 2-b). Furthermore, the performance of each PDK component has also been monitored over MPW runs with identical characterization sites. For example, the responsivities of the PDK C-band photodetector fabricated in the six MPW runs of AIM Photonics are shown in Figure 2-c. Run #1 to #6 correspond to MPW runs from 2016 to 2018 in a chronological order. The responsivity variations of the photodetectors were within ±8% over the MPW runs with a standard deviation of 2.7% (Figure 2-d). Within the same wafer, die-to-die responsivity variations of photodetectors were also measured. The responsivity varies within ±3% over different chips (shown in Figure 2-e) with a standard deviation of 1.2%, demonstrating the repeatability of the photodetector design and uniform wafer-scale fabrication.

One of the key components in the C and L band PDK component library is the 1-by-2 splitter which has two critical parameters: loss and split ratio variation. As the performance of this component improves, characterization techniques to extract these parameters begin limiting the observable performance. Loss of this device was measured using a cut-back method where the component is repeated many times to amplify the loss of a unit cell to create an increasing loss curve with respect to device repetition count (Figure 3-a). Using this technique, the silicon nitride splitter loss was measured to be less than 0.16dB over the C and L band (Figure 3-b). Furthermore, the split ratio variation of a splitter can be measured using an on-chip delayed Mach-Zehnder Interferometer (MZI) that converts the power imbalance between arms to the extinction ratio of the transmission spectrum (Figure 3-c). Simulated transmission spectra of a delayed MZI structure with different waveguide losses and split ratios are shown in Figure 3-d which points out the limitation of this measurement technique, a known loss of the optical delay is the key for extraction and a finite extinction ratio typically has two solutions. Alternatively, on-chip photodetectors have the advantage of a direct measurement of the optical power while eliminating possible variations with alignment errors or in-die variations of couplers and waveguides (Figure 3-e). As discussed above, the photodetector component in the PDK has evolved into a stable device with small responsivity variations (Figure 2-d,e). The measured imbalance between splitter arms using the detector-based measurement technique is compared to the unbalanced MZI method, showing a good agreement (Figure 3-f). The detector-based measurement was able to remove the ambiguity of MZI-based results and resolve finer features of the imbalance spectrum over multiple dies, resulting a standard deviation less than σ<0.6% (50.6/49.4 split ratio) across multiple dies (Figure 3-g).

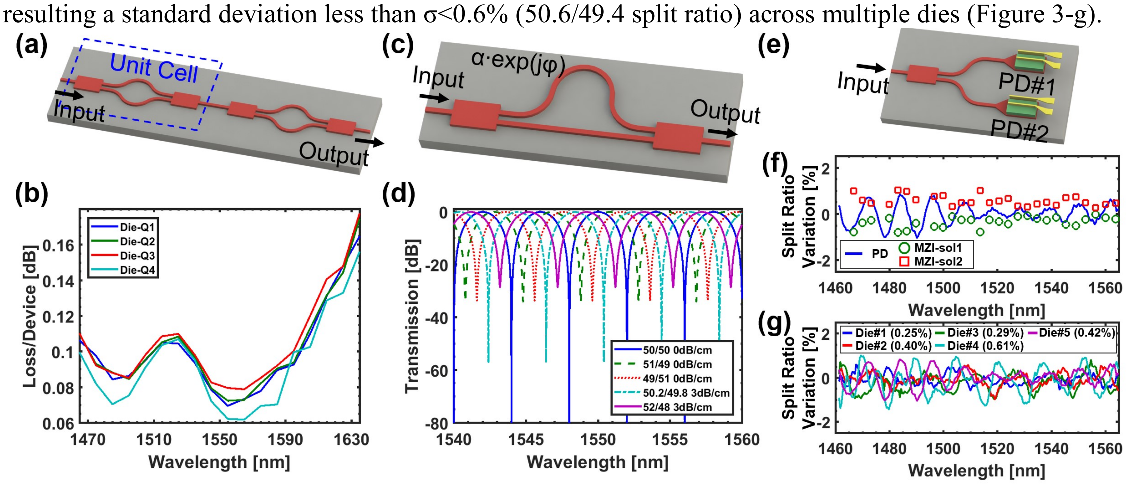

Figure 3. (a) A test structure for splitter cut-back measurement. (b) Silicon nitride splitter loss as a function of wavelength. (c) Unbalanced MZI for split ratio characterization. (d) Transmission spectra of a delayed MZI structure with respect to delay waveguide loss (150μm) and split ratio. The wavelength is offset for each spectrum for clarity. (e) Split ratio testing using on-chip photodetector. (f) Measured imbalance between splitter arms using a unbalanced MZI structure with a tunable laser and on-chip photodetectors. (g) Measured imbalance over multiple dies.

4. Conclusion

The APSUNY PDKv3.0 adds O band support to complement the verified C and L band silicon photonics library that provides state-of-the-art, repeatable performance and enables a wide range of applications using AIM MPW runs with CMOS-compatible voltages. Continued semi-annual updates will improve component performances and offer verified sub-system performance to further reduce the product time to market.

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5. References

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