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Silicon photonic components on the COTTONTAIL chip

M. Schneider,[*] B. Burger, T. Kühner and F. Simon

Institute for Data Processing and Electronics, Karlsruhe Institute of Technology, Kaiserstraße 12, 76131 Karlsruhe, Germany

E-mail: marc.schneider@kit.edu

Abstract: We report on characterization results for our new silicon photonic chip for high-speed data transmission, called COTTONTAIL (**C**hip f**o**r de**t**ector ins**t**rumentati**on** wi**t**h w**a**velength d**i**vision mu**l**tiplex). Modulation bandwidths of different travelling-wave Mach-Zehnder modulators and ring resonator modulators are sufficient for very high data transmission rates. Bit error rate measurements were conducted with a very low voltage swing of 1.1 V_{pp} and error free transmissions could be established up to a data rate of 11.3 Gb/s with the ring modulators and up to 8.5 Gb/s with the Mach-Zehnder modulators. Wavelength filters for wavelength division multiplexing show a very low transmission loss of less than 2.3 dB with a slight wavelength shift of the filtering characteristics. Also included photodiodes are well suited for high speed downlinks with data rates in excess of 40 Gb/s or on-chip modulator monitoring.

Keywords: Optical detector readout concepts; Front-end electronics for detector readout

[*]Corresponding author.

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1 Introduction

Novel optical links are required to handle the increasing data transmission bandwidth requirements and reduce the fiber count in future detectors. For this, wavelength division multiplexed (WDM) transmission systems using silicon photonic modulators with external laser sources are excellent candidates to meet the goals for bandwidth ($\gg$10 Gb/s) [1] and radiation hardness [2]. Laser sources are placed outside of the detector in low radiation areas. Therefor standard lasers for telecommunication applications with well-defined wavelengths and narrow linewidths can be used. The light of several lasers will be routed into the detector through few fibers, each transmitting a bundle of several wavelength channels. Inside the detector, silicon photonic chips demultiplex the wavelength channels, modulate data onto each one, and multiplex the bundle again for transmission to the outside. In the e.g. counting room the wavelength channels are demultiplexed again and fed into receivers for further electronic processing [2, 3].

In 2022 we developed a new silicon photonic chip, called COTTONTAIL (**C**hip f**o**r de**t**ec**t**or ins**t**rumentati**on** wi**t**h w**a**velength d**i**vision mu**l**tiplex), for optical data transmission out of detectors. The purpose of this chip is the further development of modulators towards higher bandwidths, smaller size, and lower voltage swings, test of new structures and building a usable demonstration system with at least 4×10 Gb/s transmission bandwidth. It was fabricated by imec and delivered mid December 2023. In this paper, we describe several main components of the chip and show their characterization results.

2 Chip description

The chip was developed for imec's ISIPP50G SOI platform with 220 nm nominal thickness of the optical silicon layer and approximately 211 nm real silicon thickness. The platform offers several library components, from which mainly the grating couplers, multimode interferometers as optical splitters and combiners, ring modulators and photodiodes were used. Figure 1 shows a microscope photograph of the chip, which has the dimensions 10.45×5.15 mm^2. All optical components are designed for wavelengths in the C-band around 1550 nm.

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In figure 1 several regions are marked. On the right side there are two 4-channel WDM systems made of Mach-Zehnder modulators (MZM). They include four 3 mm long MZMs, connected by a four-channel demultiplexer and an equivalent multiplexer. The two systems differ in the used MZMs, the upper one uses standard modulators with thermal phase shifters for working point control, the lower one uses radiation hardened versions of the MZMs with thicker slabs for electrical connection. Further MZMs as single components with different configurations are placed on the left side of the chip. Besides several other types, there are MZMs with 1 mm, 2 mm, and 3 mm length in a standard version with nominally 60 nm and radiation hardened versions with nominally 140 nm slab thickness.

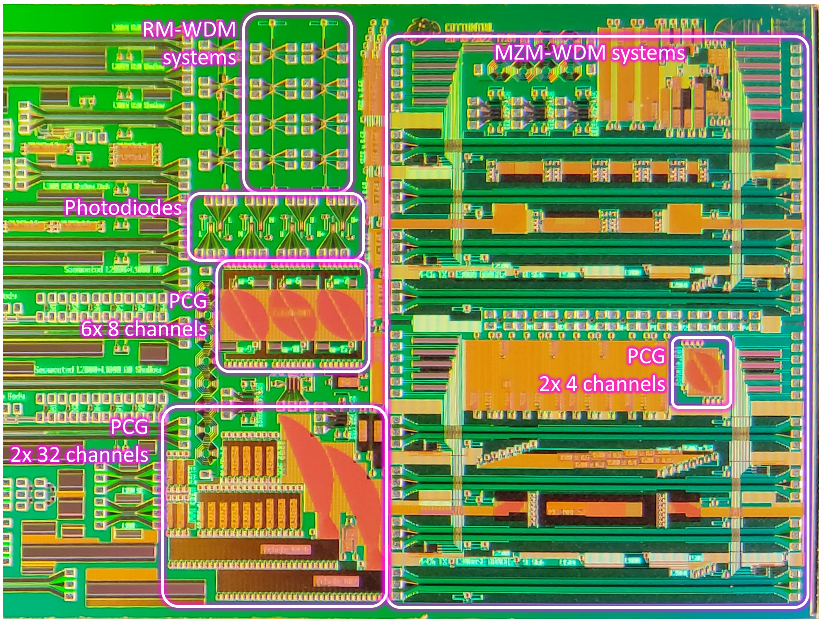

Figure 1. Microscope photo of the right half of the COTTONTAIL chip.

The same planar concave grating (PCG) (de-)multiplexers as used in the WDM-systems with a channel spacing of 800 GHz are also available as single components and marked as “PCG 2× 4 channels”. Additional PCGs with 8 channels and 400 GHz channel spacing and with 32 channels and 200 GHz channel spacing are also available for testing purposes and future systems.

Functionally comparable to the MZM-WDM systems are two ring modulator systems with four ring modulators on a single bus waveguide, marked with “RM-WDM systems”. The ring modulators (RM) are components from the imec library and the exact structure is not disclosed. Additionally, four single RMs are placed for characterization purposes to the left of the systems. The much smaller surface area required by the RMs makes them an interesting choice for future optical link systems, but they are sensitive to thermal fluctuations and process deviations and therefore more difficult to control than the MZMs.

Finally, several types of germanium-based photodiodes from imec’s library are available, a slower one for monitoring purposes and built as a lateral pin-diode, as well as three vertical pin-diodes with high efficiency, high bandwidth and ultra-high bandwidth.

Focusing grating couplers (FGC) were used to couple light into and out of the chip. The wavelength dependent loss was determined by measuring the optical transmission of waveguides of different lengths between 500 μm and 10 mm, terminated with FGCs, and using the cut-back method. The couplers achieve a minimum loss of 3.57 dB at 1554.5 nm.

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3 Results

3.1 Mach-Zehnder modulators

We characterized the different MZMs and present selected results here. Figure 2 a) shows the electrical-optical-electrical (EOE) frequency response of standard MZMs with 1 mm, 2 mm, and 3 mm length. The schematic measurement setup is shown as an inset and described in [4]. It can be seen that all curves show a steep slope at lower frequencies, followed by a rather flat portion for higher frequencies, before the curve drops again with approximately 4 dB/decade. The reason for this behavior, especially at low frequencies, is still unclear and subject of current investigations. We expected a low pass behavior with flat segment at low frequencies and a descent at higher frequencies as shown in e.g. [5–7].

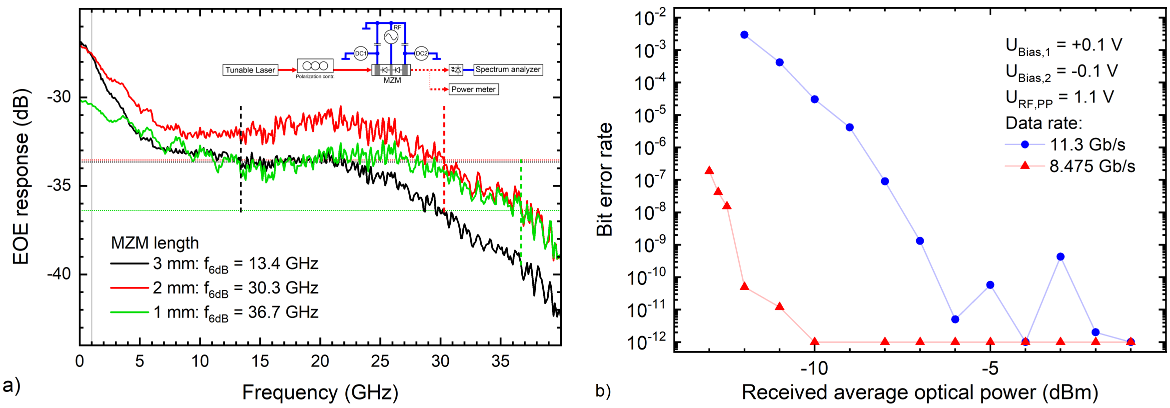

Figure 2. a) Frequency characteristics of standard MZMs of different lengths. b) Bit error rate of 3 mm long standard MZM for different data rates, measured using the receiver of an SFP+ module connected to an FPGA.

For the identification of the 6 dB cut-off frequency [8], the response at 1 GHz was used as reference. The shortest MZM of 1 mm length has an $f_{6\,dB}$ of 36.7 GHz, the 2 mm long MZM of 30.3 GHz. As the longest MZM has the largest drop, the −6 dB point lies at a much lower frequency of 13.4 GHz at the beginning of the flat region. All cut-off frequencies are high enough for a 10 Gb/s transmission, those for the shorter ones should be suitable for 40 Gb/s. We also studied the radiation hardened MZMs, which showed 6–23 GHz lower cut-off frequencies, due to a more pronounce low-frequency slope, but also suffer from a design flaw introducing high optical losses.

Following that, data transmission experiments were conducted. An FPGA board served as transmitter and as receiver for bit error rate (BER) measurements. The electrical output of the FPGA was amplified by a self-made driver, which, at the time of measurement, was unfortunately just capable of a voltage swing of 1.1 V_{pp}. The modulated optical signal from the MZM was amplified by an Erbium-doped fiber amplifier (EDFA) and attenuated by a variable optical attenuator to adjust the average optical power at the receiver side of an SFP+ module, which was directly connected to the FPGA. The measured BER for two different data rates are shown in figure 2 b) for different optical powers. For 8.475 Gb/s an error free transmission can be achieved down to −10 dBm, while for 11.3 Gb/s an error free transmission can be hardly achieved. For this data rate a higher driving voltage would be required. On the other hand, it is remarkable that data transmission is possible with such a low voltage swing, as MZMs of comparable lengths are typically driven with higher voltage swings of several volts [5, 6, 9].

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3.2 Ring modulators

The ring resonator modulators are standard types from the imec ISIPP50G library. They feature a very high bandwidth and a free spectral range of around 19 nm. Also included is a heater for thermal shifting of the operating wavelength.

We measured the EOE response of the ring modulators for different bias voltages (figure 3 a)). With a higher bias, the cut-off frequency should rise, due to the faster clearing of free carriers in the space charge region, but in all cases, it was above our measurement limit of 40 GHz.

Also here, data transmission experiments were performed with the same limitation of the driving voltage swing of 1.1 V_{pp} maximum. As expected, the ring modulators perform well with lower voltage swings and an error free data transmission with 11.3 Gb/s was possible down to −9 dBm average optical power at the receiver. From the EOE response we expect good performance even for much higher data rates, but this has to be proven with a faster driver electronics.

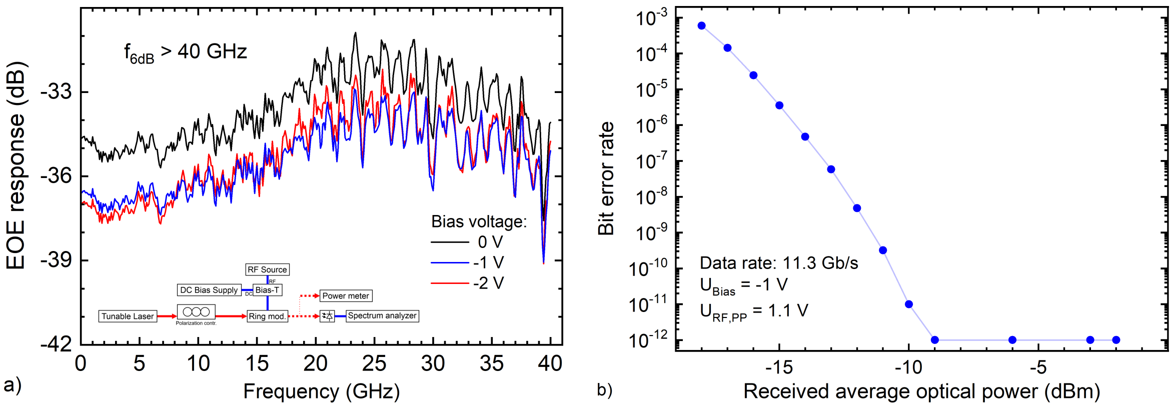

Figure 3. a) Frequency characteristics and b) bit error rate of ring modulator.

3.3 Photodiodes

Four different germanium-based photodiodes were available in imec's library, one lateral pin diode for monitoring applications and three vertical pin diodes with high efficiency, high bandwidth and ultra-high bandwidth. All types were connected to coplanar tapers from their electrical contacts to bond pads. The optical inputs were again realized by focusing grating couplers. For the characterization, two tunable lasers were mixed with correct polarization and power to achieve a 100% modulated signal. The beat frequency from the wavelength difference was converted by the tested photodiode to an electrical signal, which was measured by a spectrum analyzer. The average optical power incident on the photodiodes was −8.38 dBm.

Figure 4 shows the measured electrical power after cable and probe correction over the beat frequency. It can be seen that the lateral pin diode has the highest efficiency, but also the steepest slope. But even for the highest measured frequency of 40 GHz, the response is higher than for all other diodes. The vertical pin diodes show very similar characteristics with a slight efficiency advantage for the high efficiency type. The high and ultra-high bandwidth versions are very close together with cut-off frequencies in the range of 32 GHz. As those photodiodes should have a bandwidth in excess of 50 GHz, the contact design might be the limiting factor. This could also explain, why their behavior is so similar. But even in this configuration, they are well suited for data rates up to 40 Gb/s.

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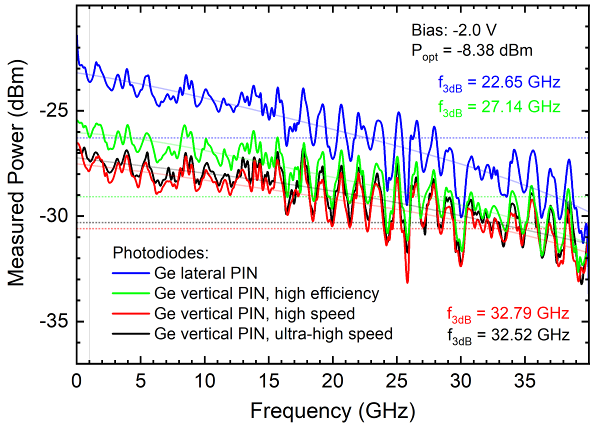

Figure 4. Frequency characteristics of photo diodes.

3.4 Planar concave gratings

The MZM-WDM systems on the COTTONTAIL chip use 4-channel planar concave gratings (PCG) as optical demultiplexers and multiplexers with a channel spacing of 800 GHz, designed using the two-stigmatic-point method [10]. For characterization, two similar PCGs are included as single components with all optical ports routed to FCGs. The transmission spectra of all channels were measured and corrected for losses of the FCGs. The design was also simulated using COMSOL Multiphysics.

Figure 5 shows the measured and simulated transmission spectra. The dotted curves are the simulated spectra, which agree very well with the designed filter wavelengths of the DWDM channels 46, 38, 30, and 22. The continuous and dashed spectra are the measurements and the peaks are all shifted by 1.7–1.8 nm to shorter wavelengths, which are approximately 200 GHz or two DWDM channels. Further simulations have shown that the shift can be easily explained by a 1.1 nm thinner silicon layer, a deviation of just 0.5% of the design thickness of 211.0 nm and well in the tolerance of the fabrication process.

As an upside, the PCGs show a very low loss of less than 2.3 dB and a low channel-to-channel crosstalk of less than −25 dB.

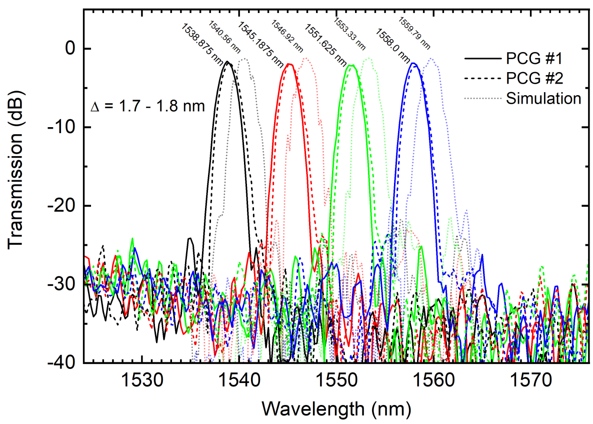

Figure 5. Transmission characteristics of 4-channel planar concave grating with 800 GHz channel spacing.

4 Conclusion

The COTTONTAIL chip shows very promising results. Standard MZMs as well as the ring modulators are fast with cut-off frequencies from 13 GHz up to more than 40 GHz. The shorter Mach-Zehnder and the ring modulators, as well as the faster photodiodes are suitable for high speed links up to 40 Gb/s, even if the photodiodes are a little slower than expected. Data transmission experiments were only partly successful, as the available driver just could deliver 1.1 V_{pp} voltage swing, which was sufficient for the RMs, but too low for the MZMs at higher speeds. The PCGs are slightly blue-shifted and it has to be determined, how random the shift is from wafer to wafer. A tuning option could also help to bring them to their desired filter wavelengths. The next steps are the characterization of the remaining components as well as radiation tests and setup of a demonstrator system.

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