Silicon Photonics for High-Speed 5G and Optical Networks

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Abstract: Optical fronthaul for radio access networks will enable the promise of 5G and beyond. We describe how centralized sources and diminutive microring modulators can meet these goals while also reducing footprint and power consumption.

1. Introduction

The deployment of fifth-generation (5G) cellular systems is enabling high bandwidth and low latency applications. Supporting virtual reality targets latency below 10 ms, and autonomous vehicles could be even more demanding. To keep latency low we can adopt a cloud-like paradigm for 5G. For instance, multi-access edge computing (MEC) is local computing power for applications with strict latency limitations. Local means physically closer to mobile units, defining the smart edge. A second strategy is to pool physical (PHY) layer processing at the same smart edge. This coordinated processing is a signature feature of 5G networks and future generations as well. Essentially, we create a radio access network (RAN) so that tower sites can share their signals for better PHY processing. We need an elastic optical access network centered on 5G systems. A RAN that incorporates a smart edge, forms a cloud RAN or C-RAN.

A silicon platform offers a smaller form factor and potentially lower unit cost for data modulation compared to lithium niobate. An all-silicon C-RAN solution is attractive as it can leverage currently established silicon photonics factory processes. As silicon photonics (SiP) is a CMOS-compatible technology based on high-index-contrast waveguides, they can also be integrated with electronic circuits in the radio frequency (RF) chain. Thus an all-silicon solution can readily integrate modulators, detectors, and other optical passive components as well as electronic components in the C-RAN. Each remote unit will be home to a high number of antennas, requiring multiple independent data streams. We consider microring modulators (MRMs) for our electro-optic conversion due to their ultrasmall footprint and low power consumption (down to fJ/bit), both superb attributes for short-reach C-RANs as we scale to larger numbers of antennas.

2. Principle

The functional splits specified in the 5G standard enables the introduction of more spectrally efficient fronthaul on optical fiber. As seen in Fig. 1, the fronthaul and backhaul converge at the smart edge. In this 5G solution using option 8 described in [1], the smart edge houses the processing power to perform coordinated baseband processing across multiple antenna sites. While the central unit (CU) focuses on network level coordination, the distributed unit (DU) handles the baseband processing. The multi-access edge computing (MEC) addresses latency-sensitive applications by putting data-center type capabilities at the edge of the network. Finally, the

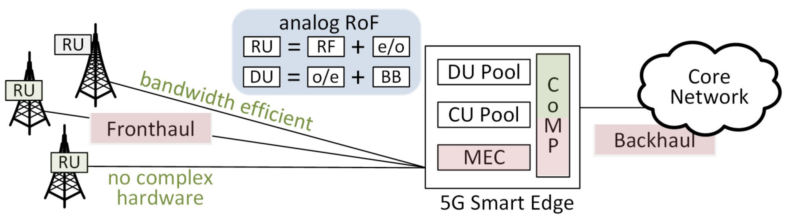


Fig. 1: Spectrally efficient, low complexity radio access network fronthaul; RF radio frequency, BB baseband, RU radio unit, DU distributed unit, CU central unit, MCU multi-access edge computing, CoMP cooperative multipoint, RoF radio-over-fiber

cooperative multipoint (CoMP) technology [2] combats inter-cell interference via RF-level coordination across antenna sites. An overview of the advantages of this architecture is available in [3].

The introduction of the smart edge enables the adoption of an optical fronthaul that is streamlined to reduce cost, enhance spectral efficiency, shrink footprint and lower power consumption. These benefits require the use of silicon photonic transceivers for the conversion of analog radio over fiber signals. In this way the radio units (RUs) at the antenna sites need only house RF components and simple electro-optic converters, i.e., modulators and photoreceivers. The smart edge has taken on all baseband processing within the DU, while the CoMP unit applies strategies to maximize wireless capacity. Both DU and CoMP require knowledge of the RF-level details of signals from each antenna site. Rather than digitizing the 5G (or 6G) RF signal, we can simply impress it on the optical carrier, i.e., analog radio over fiber. Carrying the native wireless signals this way can greatly enhance the spectral efficiency compared to legacy digital radio over fiber approaches.

Laser sources can be located at the smart edge, and the carrier distributed to the RU. The downlink signal to the RU can be suppressed by a SiP filter, and the carrier remodulated for the uplink. This allows the RU to remain simple, low cost and colorless. As latency concerns force RAN distances to be short, the carrier will not experience significant attenuation in the fiber. Several solutions exist to employ SiP subsystems that maintain reliable communications while keeping power requirements low and bandwidths high.

The wavelength selective microring resonator (MRR) filter structure in SiP provides passive filtering for the C-RAN, and the doped microring modulators (MRM) provide the electro-optic conversion. The microrings can be cascaded in a bus structure for easy signal routing. In Fig. 2 we illustrate a smart edge generating four independent signals for different antennas, each on a separate wavelength. As each ring is 10-30 μm, the structures remain small even as we scale to large numbers of antennas. The IQ structure is required for single sideband operation, as explained in the next section. Only the downlink is illustrated at the smart edge. A strong carrier is transmitted with each modulated signal.

At the remote unit we show four MRR in a cascade, each with a drop port to a different antenna. At the end of the cascade the residual carriers remain. Each of the residual carriers is modulated in turn with the uplink signals originating at the antennas. The RU could also carry several very narrowband RF signals on a single wavelength, with RF circuits that split them after opto-electric conversion. Depending on the required granularity, different configurations could be used.

3. Experimental Demonstrations for Proof of Concept

The distributed carrier requires that the previous downlink signal(s) be suppressed, followed by modulation of the residual carrier by the uplink data. In [4] we experimentally validated a silicon photonic subsystem for carrier reuse. We successfully detected five radio-over-fiber signals. The five 125 MHz RF signals were spaced at 250 MHz and occupied a total bandwidth of 2 GHz; they were detected using a single MRR drop port. The subsystem conserves a clean carrier for remodulation with good signal-to-carrier ratio. Two 125 MHz radio over fiber signals were remodulated onto the carrier with a MRM. The RoF uplink demonstrated good signal quality and performance.

Direct detection of a double sideband signal leads to power fading due to fiber chromatic dispersion especially when signal bandwidth or transmission distance increases. Using an IQ configuration with two modulators enables single sideband (SSB) modulation, and extends the transmission reach. In [5] we generated an SSB orthogonal frequency division multiplexed (OFDM) signal using an on-chip silicon photonics IQ-MRM. We achieved over 18 dB sideband suppression. The wideband signal (31.4 Gb/s) was transmitted over 20 km of standard single-mode fiber with a bit error rate (BER) below the hard-decision forward error correction threshold at 3.8×10^{-3}.

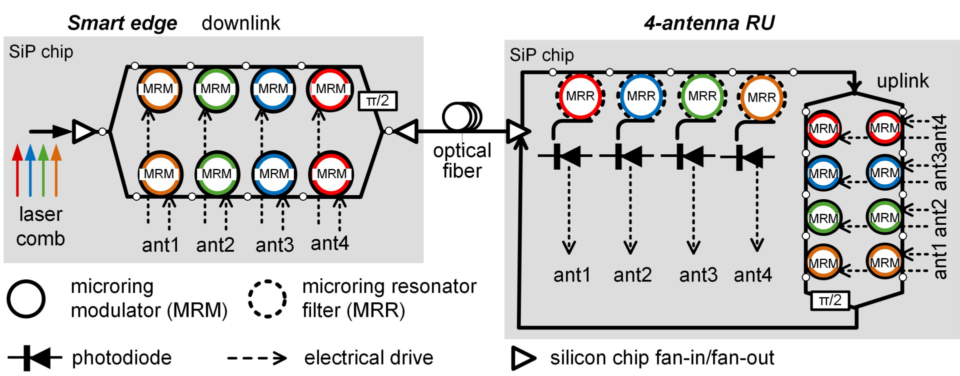
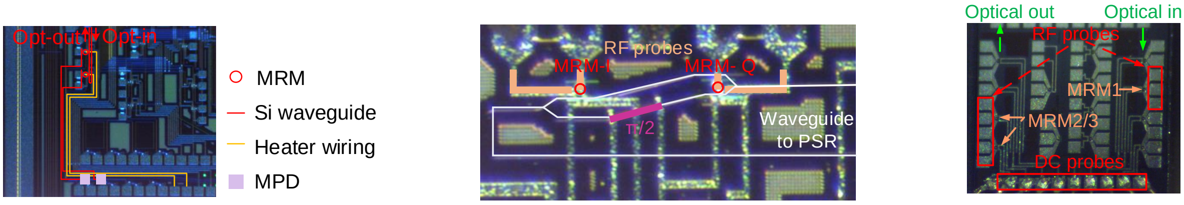


Fig. 2: Distributed carrier for wavelength selective drops to individual antennas, and remodulation for the uplink



(a) (b) (c)

Fig. 3: Photos of fabricated chips a) with on-chip photodetectors for stabilization [7], b) with polarization insensitive modulation [6], and c) used in WDM experiments [8]

In these previous experiments we manually controlled the signal polarization to be aligned to the TE mode for compatibility with the SiP waveguides. For remodulation of the distributed laser it is essential to have a SiP subsystem that can handle any arbitrary polarization. In [6] we experimentally demonstrated a polarization-insensitive SSB modulator based on MRM. The modulator split and modulated the two orthogonal polarization states of an input laser in a loopback structure. The adoption of MRM bypassed the bandwidth limitation by the mismatch of electrical and optical waves of travelling-wave electrodes, in polarization-diverse versions of SiP Mach-Zehnder modulators (MZM). Our experiments validated the proposed modulator polarization insensitivity and transmission performance.

While our illustration in Fig. 2 shows a cascaded ring for one RU site, we could use wavelength division multiplexing (WDM) across RUs. In [8] we showed that MRM have the tunability and free-spectral range to cover wide wavelength bands. The 10 μm-radius MRMs in our experiment had a free spectral range of 10 nm, covering 30% of the C-band. In each wavelength slot we created three disparate signal types (very wideband digital signal, and analog narrowband radio over fiber signals in baseband and on a 3.5 GHz carrier). We were able to generate these signals with MRMs tuned within the WDM slots examined. Reception at each wavelength slot showed good performance.

The wavelength selectivity of the MRM relies on temperature tuning. The working wavelength drifts with temperature variations. We demonstrated an on-chip monitoring photodiode at the drop-port of MRM [7]. With this we are able to monitor the dropped optical power during modulation. We demonstrated good stabilization with simple feedback control at very low frequency.

The spectral efficiency of the distributed carrier system can be extremely high. In [9] we reported an MRM transmitter achieving channel spacing comparable to the symbol rate in each WDM channel, reaching a spectrum occupation of 80%. By choosing the correct operating point, we demonstrated no discernible interchannel interference power penalty.

4. Conclusion

We have discussed the advantages of the adoption of option 8 in the 5G standard that assumes the simplest hardware at remote antenna sites: a simple electro-optical conversion. By carrying an analog radio over fiber signal, spectral efficiency can be high for the demanding fronthaul that must support many antennas at each remote site. At the same time, the use of silicon photonics can keep costs down both in the remote radio unit and the smart edge where RF processing is centralized.

References

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