Optical Multilevel Signaling for High Bandwidth and Power-Efficient On-Chip Interconnects

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Abstract— **The scalability of high-performance computing systems is increasingly dependent on high-bandwidth and power-efficient communication between a growing number of processing cores on- and off-chip. Recent developments in silicon photonics technology can potentially alleviate many of the challenges associated with these stringent interconnection demands. In this letter, we propose the use of an optical multilevel signaling technique for on-chip interconnects in conjunction with wavelength division multiplexing to double the aggregate communication bandwidth without increasing the number of waveguides and wavelengths used, thereby reducing scaling costs.**

Index Terms— **Optical interconnections, photonic integrated circuits, amplitude shift keying.**

I. Introduction

MONOLITHICALLY integrated silicon photonics as a promising technology can offer high bandwidth and better power efficiency for interconnection networks [1]. Multiple wavelengths can share a waveguide without interference by leveraging wavelength division multiplexing (WDM) transmission schemes, resulting in high bandwidth density — as much as 1 terabits per second (Tb/s) in a single waveguide [2]. Recent advancements in photonic devices such as high-speed optical modulators with data rates up to 25 Gbps and multi-mode waveguides using mode-division-multiplexing (MDM) [3] have significantly extended bandwidth scaling. However, these novel approaches increase the fabrication complexity.

Current on-chip optical interconnect schemes use on-off keying (OOK) modulation that utilizes the presence and absence of a carrier wave to represent logical 1 and 0, whereas, Optical Multi-Level Signaling (OMLS) modulation increases the data rate by compressing multiple bits into one symbol, carried by multiple levels of amplitude [4]. In doing so, OMLS has the potential to provide much higher bandwidth as compared to OOK technique. Other important modulation techniques used in optical interconnects are discussed in detail in [5]. Because OMLS offers low implementation complexity of all modulation techniques, it is more suitable for high bandwidth on-chip interconnects.

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OMLS technique has been traditionally implemented widely for off-chip interconnects using phase shifter Mach-Zehnder modulators. However, this implementation approach is not suitable for chip multiprocessor design as it requires a substantial amount of chip area, usually in millimeter scale [2]. Recently, a compact Mach-Zehnder-type modulator based on microring resonators (MRRs) that generates multiple amplitude level signals has been demonstrated [6]. The basic components of this modulator are MRRs and the modulation does not rely on the large footprint phase shifter, as such it is possible to integrate with multiprocessors on the same chip.

In this letter, an on-chip OMLS link based on MRRs and an adaptive power management technique are proposed. We illustrate the transceiver design of the proposed scheme at circuit level to evaluate the potential benefits. Our simulation results show that the on-chip OMLS interconnect can double the bandwidth of each wavelength and thus improve overall network bandwidth while requiring less chip area and fewer wavelengths. We also describe an adaptive power management technique to mitigate the slight increase in power consumption.

II. Proposed On-Chip OMLS Implementation

In this section, we first describe a brief background of the optical photonic technology used for on-chip interconnects, and then present the detailed implementation of OMLS.

A. Silicon Photonic Technology

Fig. 1(a) depicts a conventional photonic link with four wavelengths onto the same waveguide. The photonic devices can be fabricated on a silicon-on-insulator (SOI) substrate with a thick buried oxide layer. The interconnection brings electrical data signals into the optical domain, transmits them along the waveguide, and converts the optical signals back to the electrical domain at the receiver side. Multiple wavelengths can be transmitted simultaneously over a single waveguide to provide tremendous bandwidth through WDM.

The laser source can be on-chip or off-chip [7]. In case of off-chip laser, light is coupled into an on-chip waveguide and should be modulated by a separate modulator to encode data. A MRR functions as a modulator with specific resonance wavelengths [8]. The resonance wavelengths correspond to both the ring circumference and the effective refraction index of the ring waveguide. Since the ring can be fabricated in a depletion-mode structure, the effective refraction index can be fast tuned by changing the charge carrier

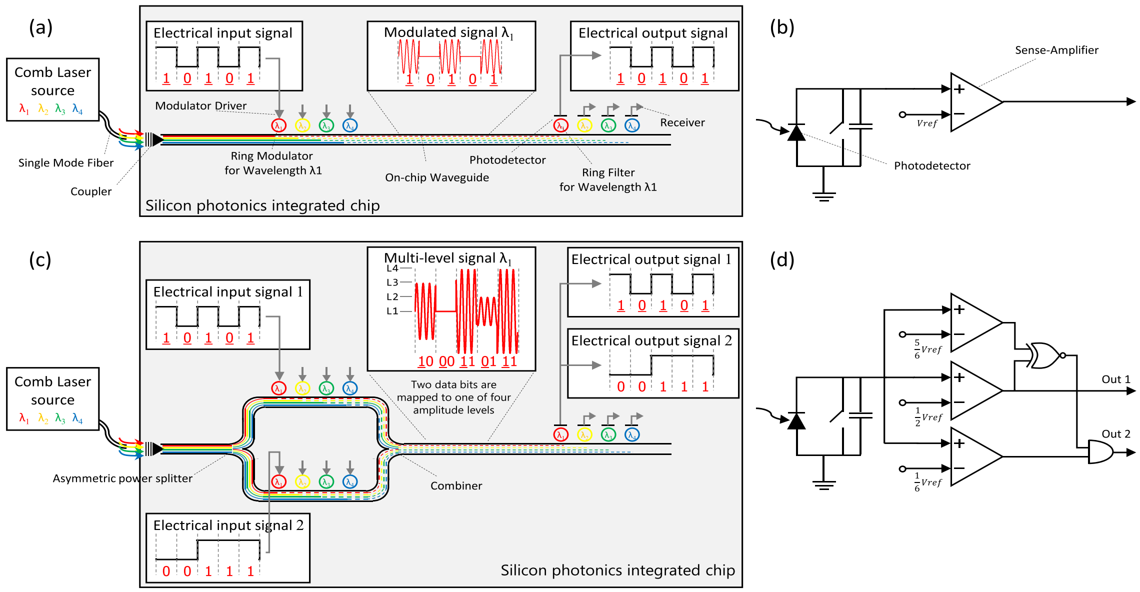

Fig. 1. (a) The conventional photonic link. (b) The current-integrating receiver. (c) The Optical Multi-Level Signaling (OMLS) link. Example of encoding a four-amplitude-level signal into a single wavelength with two input binary signals and OMLS receiver using (d) a modified current-integrating receiver.

concentration electrically. In case of on-chip laser, the laser source can be modulated directly by switching on and off since it is closely integrated with the control circuit. Because of this flexibility, the energy efficiency can be optimized [7].

Another major component commonly used in optical interconnects is the optical power splitter [9], [10]. The optical power splitter, such as multimode interference or Y-junction splitters can distribute the incoming light from all wavelengths of one waveguide into multiple waveguides.

At the receiver side, rings are tuned to select each specific wavelength. Each ring is then connected to an optical receiver to decode the data. The optical receiver is composed of a photodetector (PD), a receiver circuit and a ring tuning circuit. The current-integrating receiver circuit is shown in Fig. 1(b). This type of receiver circuit provides better photocurrent sensitivity than other traditional optical receivers due to its low parasitic capacitance [11].

Due to process mismatch and temperature variation, the resonance frequency of rings is shifted by a certain amount resulting in higher ring tuning power because rings have to tune back to their assigned resonance frequency. To compensate for these mismatches, a ring tuning circuit (not shown in Fig. 1) with the bit re-shuffling technique [11] can be used.

B. Proposed OMLS Link

Fig. 1(c) describes an implementation of an OMLS link. A 2-way asymmetric splitter is placed at the transmitter side diverting one third of input laser power to the lower waveguide and the rest remains in the upper waveguide. Therefore, the upper waveguide dominates a larger amplitude power than the lower waveguide. Each waveguide includes an identical series of rings modulating the same set of wavelengths simultaneously. We show four wavelengths for demonstration purposes, but up to a hundred of wavelengths can be accommodated in single waveguide using WDM technology [1]. OOK modulation is used for both upper and lower waveguides simultaneously. After modulation, a combiner at the end of the transmitter merges these two optical signals back to one four-amplitude-level signal, commonly known as a 4-ASK signal. Each amplitude level represents one of the four combinations of two bits. For example, if the upper signal is 1 and the lower signal is 0, the merged signal becomes the third amplitude level (10).

The light propagates through the ring to a PD at the receiver. In the backend electrical circuit of the receiver, we use a modified current-integrating receiver with three sense-amplifiers and two logic gates to decode the 4-ASK signal, as shown in Fig. 1(d). The photocurrent induced by the PD is integrated onto the capacitor and the capacitor must be reset to an initial value at the beginning of each integration. These sense-amplifiers, having different reference voltages, compare the voltage on the capacitor with their reference voltage. The original data are eventually decoded back at the output of the receiver circuit.

In this letter, we assume all photonic devices are monolithically integrated. Although 3D stacking is a popular emerging technique and provides more flexibility, it comes with a high manufacturing cost due to the additional demand on dies and through-silicon-via implementation. We also assume upper and lower waveguides at the transmitter present identical phase delay, so two modulated lights can be combined without destructive interference.

The proposed OMLS can be used in various scenarios to boost bandwidth, and reduce area and cost as follows:

1) *Bandwidth:* For high performance computing system, the use of OMLS links can effectively double the aggregate bandwidth while using the same numbers of wavelengths and links as compared to conventional optical interconnects.

2) *Area:* If the area consumption is the major constraint in the target system, OMLS link can be used to half the number of long-distance waveguides and fibers: two conventional links

TABLE I

OPTICAL TECHNOLOGY PARAMETERS

Parameter	Value	Unit
Laser Efficiency	30	%
Waveguide Pitch	4	μm
Waveguide Loss	1	dB/cm
Coupler Loss	1	dB
Splitter Loss	0.2	dB
Ring Drop Loss	1	dB
Ring Area	100	μm^2
Receiver Responsivity	1.1	A/W

can be replaced by one single OMLS link to achieve the same bandwidth performance.

3) *Cost:* The proposed OMLS scheme can also be used for reducing the cost of laser sources. If the number of links remains unchanged, the laser sources only need to generate half the number of wavelengths to achieve the same bandwidth, resulting in less expensive laser devices.

III. EVALUATION

We compare the proposed OMLS link with the conventional link in three different aspects: bandwidth, energy and area. All devices are based on a 22nm processing technology. To evaluate energy consumption, we extended the photonic model of the DSENT simulator [12] to include the OMLS link. The parameters of the optical components are listed in Table I for our analysis.

A. Bandwidth

We make the following assumptions to evaluate the bandwidth. Up to 128 wavelengths can be placed on a waveguide by transmitting wavelengths on opposite directions [1]. And the ring with a 4 – 5 THz free-spectral range is used, capable of modulating one specific wavelength [7]. For a fair comparison, the total optical transmission latency of both links is assumed the same (3 cycles), including one cycle of electrical to optical conversion, one cycle of waveguide propagation and one cycle of optical to electrical conversion.

Fig. 2 shows the comparison of bandwidth under different numbers of wavelengths. A single OMLS link with rings modulated at 10 GHz can achieve a maximum bandwidth of 2.56 Tb/s, whereas a conventional link is only half of that.

B. Energy

Energy consumption includes both electrical power and optical power. Electrical power is composed of the power from backend circuits that are used for modulator driver, sense-amplifier, associated Serializer/Deserializer (SerDes) and bit re-shuffler. The optical link consumes laser power and ring tuning power. For ring tuning power, we assumed that using the depletion-mode ring can be tuned electrically. Regardless of whether the laser power is on- or off-chip, the required laser power is determined by the amount of optical losses as it propagates along the path and the sensitivity at the receiver:

$$P_{laser} = P_{rx} \times 10^{C_{loss}/10}$$

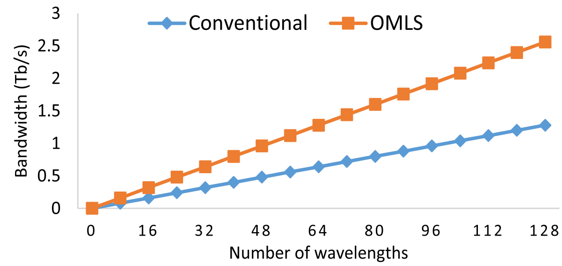

Fig. 2. The bandwidth of one singular link using both approaches.

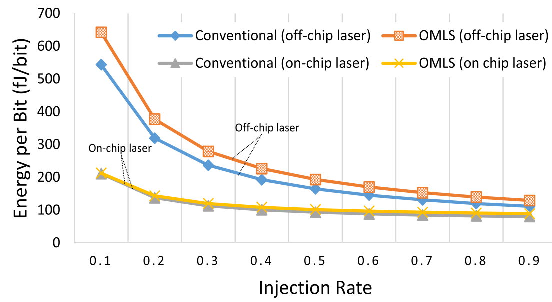

Fig. 3. Optimized energy consumption vs. injection rate of a link with 640 Gb/s bandwidth for different approaches.

where P_{rx} is the minimum detectable laser power required at the receiver and C_{loss} is the summation of link losses including the modulator insertion loss, given in dB. P_{rx} is related to the photodetector responsivity and the modulator extinction ratio calculated by equations in DSENT.

OMLS requires 4.8dB more laser power at the receiver circuit to differentiate the four-amplitude-level signal [4]. Furthermore, due to the two additional sense-amplifiers, the parasitic capacitor increases, resulting in increase of photocurrent and laser power required.

Laser power can be reduced by increasing modulator extinction ratio and decreasing insertion loss. However, this approach increases the modulation power. Optimization is made in every simulation to obtain the minimum energy consumption. Since laser power is the dominant factor of energy consumption [12], we also evaluate links with on-chip lasers to optimize energy consumption. The modulation rate of a ring is set to be 10 GHz to attain optimal energy efficiency [11].

In Fig. 3, in case of off-chip laser, the energy consumptions of OMLS and conventional links have higher differences at low injection rates than at high injection rates. There is an 18% increase at most in energy consumption. The reason is that the efficiency of laser power increases and its dominance decreases as the injection rate increases. In case of on-chip laser, the energy consumptions are similar at low injection rates because the lasers are throttled when they are not in used, but the differences increase at high injection rates.

C. Area

Fig. 4 shows the area breakdown of photonic components that includes waveguide and ring. We assume each link is 4 cm long and used for on-chip global interconnections because many modern multi-core chips are commonly considered to be

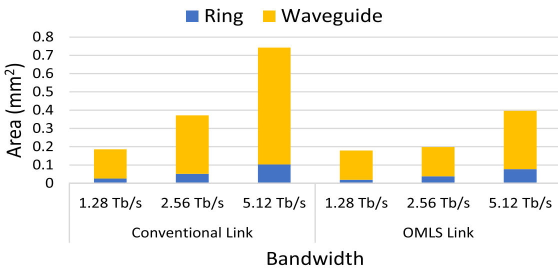

Fig. 4. Area consumption of different bandwidths.

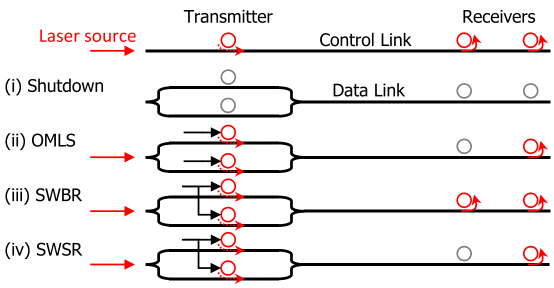

Fig. 5. Adaptive power management for the proposed OMLS link. The upper first waveguide is the control link and the lower waveguides are the data links with four operation modes respectively. The colored circle represents that the ring is tuned in and gray represents that it is tuned out.

400 mm^2 [1]. To offer bandwidth at 1.28 Tb/s, both approaches require only one waveguide hence they take up similar space, however OMLS requires half the number of wavelengths. As the number of wavelengths reduces, the number of rings required at the receiver is also reduced. To offer bandwidth at 2.56 or 5.12 Tb/s, the conventional approach requires double the number of links to achieve the same bandwidth as OMLS due to the fact that each waveguide can only transfer 128 wavelengths at most and OMLS can double the bandwidth of each wavelength.

IV. Adaptive Power Management Scheme

The analysis above reveals that the energy per bit increases for the OMLS link. To alleviate this problem, we propose an adaptive power management scheme. With this adaptive power management, the OMLS link can switch between different modes based on the traffic load and the required performance to avoid excessive power consumption without physically changing the layout.

We assume the adaptive power management can be used on the link that has single transmitter and multiple receivers. Only one additional control link using OOK modulation is required to control dozens of data links. The control link broadcasts messages to direct all other receivers to turn on or off on its data links before sending the data. In Fig. 5, the OMLS link can switch between four operation modes to manage power consumption:

1) *Shutdown Mode:* The laser source of the data link is turned off and the rings are unbiased when no data is transmitted. There is no power loss in this mode.

2) *OMLS Mode:* This mode uses OMLS modulation to double bandwidth as mentioned previously. The control signal specifies which specific receiver to be tuned in. Only that receiver can receive the data to ensure minimal signal loss to successfully decode a signal.

3) *SWBR Mode:* Single Write Broadcast Read mode uses binary signaling to send broadcast messages to all or part of the other receivers. It requires much higher laser power in this mode according to the number of receivers because each receiver requires a minimum signal power and they share the overall available power.

4) *SWSR Mode:* This is a conventional Single Write Single Read mode using binary signaling with one receiver tuned in suitable for low link utilization. When sending binary signals in modes 3 and 4, two input signals (upper and lower waveguides) should be identical, resulting in only two amplitude levels (both one or both zero).

We plan to integrate OMLS and the adaptive power management technique into a system architecture and assess its benefits using real network traffic and benchmark suites.

V. Conclusion

In this letter, we propose OMLS as an on-chip optical interconnect that can be monolithically integrated. Through physical simulation, we show that OMLS has the potential to improve bandwidth, area and cost as compared to conventional optical interconnects. However, there is a slight increase in power consumption, which can be remedied with an adaptive power management technique.

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