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Invited Papers

Development trends in silicon photonics for data centers

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ABSTRACT

An explosive increase in volume of global network and data center traffic requires an interconnection scheme with low cost, high energy efficiency, and high bandwidth capacity. The optical interconnects, especially utilizing silicon photonic platform, have been widely proposed to meet this challenging requirement as they intrinsically feature strong promise to obtain a high bandwidth and power efficient short-reach interconnection in much lower cost. In this review, we will discuss the current development trends in silicon photonics for datacenter application with emphasis on reducing cost, lowering energy consumption, and increasing capacity.

1. Introduction

The previous decades have witnessed an explosive increment in the volume of global network traffic. The amount of annual global data center traffic in 2015 is already estimated to be 4.7 Zettabyte (1021 bytes) and will triple to be 15.3 Zettabyte by 2020 [1]. The data-intensive applications such as streaming video, social networking and cloud computing require the data center to provide extremely high bandwidth communication. Transporting such increasing volume of data with existing technologies such as the conventional metallic interconnects, as they are limited by the finite resistance and capacitance, will soon reach its limit and therefore will not be able to satisfy the exponentially increasing capacity demands. Meanwhile, the scale expansion of the datacenter will also consume huge power. So, efficient interconnection scheme with low cost, high energy efficiency and high bandwidth capacity is in great need. Optical interconnects, especially utilizing silicon photonic platform features strong promise to obtain a high bandwidth and power efficient optical interconnect [2,3]. Although the market sales for silicon photonics in 2015 was below 40 million dollars, a dramatic growth will begin in 2018 and the estimated market sales for silicon photonics in data centers will reach about 1.2 billion dollars by 2025 (as shown in Fig. 1), within which the predicted packaged silicon photonics transceiver market will occupy about 6 billion dollars in ten years [4]. What's more, the projection indicates that silicon photonic interconnects will out compete metallic and multimode-fiber interconnects as their cost reduces to 1$/Gbps. In this review, we will discuss the current development trends in silicon photonics for datacenter application with emphasis on low cost, low energy consumption and increased capacity.

2. Data center optical interconnection and silicon photonics technology

2.1. Data center short-reach interconnects

The optical interconnection inside data centers covers a range of 0–10 km [5]. The shortest reach is favorably dominated by VCSEL (Vertical Cavity Surface Emitting Laser) transceiver (III-V material, SWDM standard) whose advantages originate from its structural hermeticity, large alignment tolerance, the compatibility with low-cost plastic coupling systems, and the ability to operate without optical isolation. Such interconnects traditionally extended to 0–100 m but OM4 multimode fibers and newly developed techniques may potentially support up to 400 m reach under 25 Gbps bit rate [6]. Above VCSEL-dominated distance, single-mode fibers are necessary where silicon photonics play a pivotal role. From this perspective, silicon photonics and VCSEL technology are complementary rather than competitive. The scope of this paper is therefore confined to interconnection of > 400 m reach in data centers.

The data center interconnection falls into the category of IEEE 802.3 standards: currently 25 Gbps and 28 Gbd per lane, intensity modulation and direct detection (IMDD). Four specific 100 G MSAs were proposed by different alliances of companies, namely parallel single-mode 4 lane (PSM4) [7], CWDM4 [8], CLR4 [9] and Open Optics multisource agreement (MSA) [10]. It is likely that PAM-4 will be supported in the standard of the next generation (e.g. IEEE 802.3bs and 802.3cd) while maintaining the current 28 Gbd symbol rate.

Table 1 lists the four standards and some of the important specifications. Since much greater volume is demanded in data center

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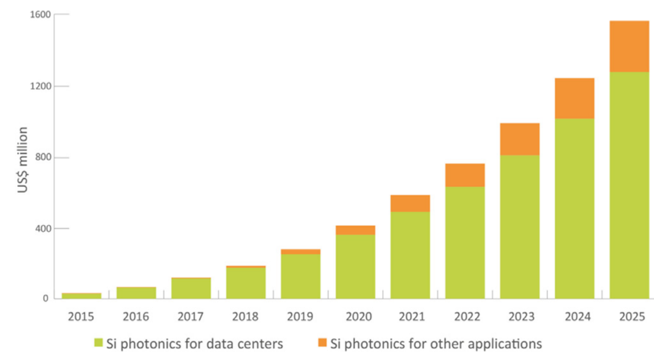

Fig. 1. Silicon photonics market forecast for data center [4].

interconnection than longer range communication, cost is vitally important in terms of feasibility. The use of IMDD and forward error correction (FEC), in the context of short-reach transmission, considerably relaxes the requirement of signal quality and thus of device performance. Extinction ratio as low as 3.5 dB and 2.5 dB are acceptable. PSM4 is the most straightforward method, increasing capacity simply by adding more lanes. The technical simplicity helped the emergence of some of the first data center commercial products. Nevertheless, fiber cost ramps up rapidly with interconnect distance. The other three MSAs tackle this issue by Wavelength Division Multiplexing (WDM). CWDM4 and CLR4 employ coarse wavelength division multiplexing (CWDM) at 1310 nm band, the channel spacing of which is sufficiently tolerant even for silicon multiplexers without temperature control. Open Optics operates at 1550 nm, with future scalability of Dense Wavelength Division Multiplexing (DWDM). As fabrication technology the III-V on silicon laser technology as demonstrated by Intel grow mature, the use of WDM can be expected to bring down the cost while providing reliable interconnection, just like it has been in long-range fiber communication systems. It is likely that PAM-4 will be supported in the standard of the next generation (e.g. IEEE 802.3bs and 802.3cd) while maintaining the current 28 Gbd symbol rate.

2.2. Silicon photonics solution for data centers

Silicon photonics leverages complementary metal oxide semiconductor (CMOS) IC technology which has brought about dramatic changes to the world by its large scale integration, wafer scaling, high yield production, and low cost processing capabilities [11] and its high functionality in processing, memory and many other areas. Specifically, it allows the incorporation of a number of materials, known as CMOS-compatible materials, including silicon dioxide, Germanium, silicon nitride, titanium oxide, etc. Besides the advantages granted by CMOS technology, silicon photonics possesses other three major favorable characteristics: high refractive index difference between silicon and oxide which shrinks device dimensions and improves integration density; readily available Si/SiO_2 passivation processing that yields high-quality interfaces; non-hermetic packaging supported by silicon photonics materials which saves both in cost and fabrication time.

The key functionalities in data center interconnection are lasing, modulation, wavelength multiplexing and detection (As shown in Fig. 2). Silicon photonics solution provides these functionalities in a monolithic fashion except that lasing usually requires hybrid integration of III-V materials. Solutions in QSFP28 form factor (power < 3.5 W, 35 pJ/bit) provided by silicon photonics have been commercially available. Luxtera and Mellanox are two leading suppliers to announce silicon photonics products. Currently, hybrid laser is either achieved by bonding a III-V packaged DFB/DBR laser, or by bonding III-V material in front end of line (FEOL) and then patterned by wafer-scale processing (Intel and Skorpios [12]). The latter is technically more challenging, but yields higher integration density and lowers costs. Germanium EAM has gained more attention over the years, yet silicon material itself also has the potential for low energy consumption modulators. Multiplexers made of silicon or silicon dioxide can well meet the demand of CWDM channel spacing without the need for temperature control [13]. Ge detectors have been rather mature and reliable in the 1310 nm and 1550 nm communication bands. To power the photonic integrated circuits (PICs), electrical drivers are normally separately fabricated and flip-chip bonded onto PCB or directly onto the optical chip. Higher integration level of silicon photonics is likely to have the PICs and the electrical drivers monolithically integrated on a single chip [14].

In short, silicon photonics technology is well capable of providing data center optical interconnection solutions and several products are already commercially available. Among various link lengths, the ones over 500 m are suitable for silicon photonics while shorter range remains III-V based MMF links. Technical maturity and system performance are constantly improved owing to the continuous effort from both academia and industry, especially the development of heterogeneous integration of lasers is expected to bring substantial impact to the field. Three major development trends will be detailed in the following sections.

3. Development trend 1: reducing cost

Current silicon photonics technology has been viewed as a critical solution to the next generation datacom system. The increment of communication within datacenters has brought about the increasing number and reach of optical links. Although the well-established III-V process technologies still play a dominant role in datacenters, drawbacks on limited wafer size and poor compatibility with the CMOS integrated electrical circuits will restrict its ability for high-density and high-capacity applications in the long term. In contrast, optical interconnections via silicon photonic technology owns the potential for bringing large wafer size and volume throughout, which paves the way for low-cost intra datacenter communication. But for all the time, the main drawback of silicon photonics lies in the lack of reliable on-chip laser. The off-chip laser maybe an alternative but the resulting optical packaging will increase the cost and make silicon photonics lose its favor. Many researches have been initiated for on-chip lasers, such as silicon hybrid lasers [16–20,24] and optical amplifications in Er/Yb silicate [25,27]. However, before fully developing the low-cost potential of silicon photonics, laser integration on silicon platform is the most important issue to be solved, because it can decrease the number of the discrete components and thus simplify the optical packaging. So in this section, more emphasis is placed on the progress of laser integration on silicon platform.

Table 1
100 G Multisource agreement standards for short-reach interconnects.

	Duplex cores	WDM type	Wavelength	Reach	Link budget	Min ER	Min OMA, each lane
PSM4	8	–	1310 nm	500 m	3.26–14.66 dB	3.5 dB	~ −6 dBm
CWDM4	2	CWDM, 4λ	1310 nm	2 km	5.0–14.0 dB	3.5 dB	−4.0 dBm
CLR4	2	CWDM, 4λ	1310 nm	1–2 km	3.5–12.5 dB	3.5 dB	−4.0 dBm
Open Optics	2	DWDM	1550 nm	2 km +	> 5 dB	2.5 dB	−7.0 dBm

*Open Optics channel grid is multiples of 200 GHz. Specifications are at the presence of FEC [10].