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Survey on Silicon Photonics

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Abstract: *Silicon Photonics is a relatively new field with the goal of developing silicon based optical devices. This approach appears to be very enticing due to multiple reasons including the large established silicon fabrication infrastructure and the relatively low cost and high abundance of this material [1]. The future of IC industry depends upon the speed and bandwidth requirements, but in metallic interconnections we have constraints on speed as well as bandwidth. This paper reviews the growth of silicon photonics compared to last few years and a promising future of photonics.*

In 2008 Intel declared that the data transfer rate can be increased further up to 1Tbps (bits per second). Researches at Intel developed Silicon based lasers like Hybrid silicon laser in Sept2009, modulators with 40Gbps(2007), multiplexer, demultiplexer, Basic light routing components like waveguides, couplers, light detectors like avalanche photodetector (2008). Intel have successfully demonstrated the complete 50Gbps data link using silicon photonics and integrated lasers[2] and going forward to develop high volume manufacturing process for silicon photonics and to bring high bandwidth, low cost optical communication in and around future PCs, servers and consumer devices. This paper gives information about silicon platforms and silicon optical devices which are successfully demonstrated by researchers.

Keywords: *Integrated waveguide, Optical Isolator and Circulator, Optical Tranreceiver, Silicon-on-Insulator, Tunable laser*

I. Introduction

Silicon photonics is a new technology of producing optical devices and circuits using silicon as core material for the integration of optical and electronic components on single chip with standard CMOS (complementary metal oxide semiconductor) fabrication process. Silicon is the second most (after oxygen) abundant element on earth. With a simple cubic crystal structure, silicon can be used to make wafers with incredible purity without defects. In addition, silicon's large thermal conductivity, hardness, and low density are useful in semiconductor devices. Silicon has a high refractive index of 3.476 at 1550 nm and is transparent to infrared light with wavelengths above approximately 1100 nm. The property of the high index promotes the downscaling of device footprint to the order of submicron and nanometer sizes. Moreover, the mature complementary metal–oxide semiconductor (CMOS) processing techniques are readily applicable to silicon photonics for low-cost mass production. Furthermore, silicon's high quality native oxide, SiO2, offers one of the major advantages of silicon over germanium and other semiconductors for integrated circuits. By virtue of its optical properties, such as the relatively low refractive index (nSiO2 = 1.45 at 1550 nm) and the optical transparency in the telecommunication wavelengths, the oxide could serve not only as a good silicon waveguide cladding material, but also as an excellent host material for rare-earth dopants. Additionally, the control of the oxide cladding layer could introduce stress-induced waveguide birefringence, thus manipulating light propagation in the enclosed silicon waveguides. All these factors make silicon photonics a promising candidate for photonic circuit integration. The basic building block of silicon Photonic Integrated Circuit (PIC) includes silicon-based lasers, silicon waveguides, silicon modulators, and detectors. The light generated by each silicon-based laser is transmitted to the modulator through the waveguides. The silicon modulator then encodes a signal into light, which in turn is carried by additional waveguides to propagate to their destination, silicon photodetectors, where the optical signals are converted into electronic signals for post-processing. During the past three decades, the first stage of the silicon photonics research was primarily focused on the proof-of concept devices and building block circuits, solving the most stringent problems such as fiber-to-waveguide coupling, and creating similar photonic components developed on other material platforms (i.e. InP, GaAs, and polymer) [3-6]. Nowadays, researchers are shifting their efforts towards the optimization of the existing components and the expansion of the functionality sets.

To date, silicon photonics is still considered an emerging area. Various review papers [1] presented different aspects of silicon photonics and its future aspects. However, very few review articles have discussed the early work on silicon photonics from 2013. This review covers the nearly research work and offers an overview of the critical breakthroughs in the field.

II. Silicon Platforms

Silicon photonics typically builds on silicon-on-insulator based high-index-contrast waveguide system. Silicon nitride provides an alternative moderate-index-contrast system that is manufacturable in the same CMOS environment. This paper discusses the relative benefits of both platforms [7].

2.1 Silicon On Insulator (SOI) Vs Silicon Nitride (SiN)

We discuss the key properties of a SiN-based PIC platform in comparison to the SOI-based PIC-platform.

Transparency range: SOI-based waveguides have low absorption losses in the wavelength range from 1.1 μm(Band edge of silicon) to about 3.7 μm (onset of mid-IR absorption of silica). For applications requiring shorter wavelengths (e.g. data communication at 850 nm, sensors operating in the therapeutic window etc.) SOI is not an option. Since SiN is transparent throughout most of the visible range – down to at least 500 nm – it is a viable candidate to implement "silicon photonics" at wavelengths below 1.1 μm [7]. This has led to demonstrations of spectroscopic functions [8-9], Raman spectroscopy-on-chip functions [10-11] and integration with colloidal quantum dots emitting in the visible

Index contrast: The index contrast in SOI waveguides (cladded with silica) is very high (3.5 vs 1.5) while that in SiN waveguides (cladded by silica) is moderately high (2 vs 1.5). The lower index contrast of the SiN system as compared to SOI implies that it is harder to make high efficiency grating couplers for out-of-plane optical input/output, a very useful feature that allows for wafer-level testing and alignment-tolerant fiber coupling [12]. Nevertheless grating coupler efficiencies below 3dB have been reported.

Low loss: SOI-based photonic wires – silicon strip waveguides completely surrounded by a silica cladding – have typical waveguide losses of 1 to 2 dB/cm, largely due to the scattering losses associated with sidewall roughness. Losses down to ~1 dB/m have been reported for such SiN waveguides [13].

Manufacturing flexibility: SiN is deposited by LPCVD or PECVD and that implies that there is a lot more flexibility to combine the SiN waveguide with other photonic structures than is the case for SOI.

Third order nonlinearity: The Kerr nonlinearity of silicon is huge but unfortunately it is useless in the 1300/1550 telecom bands because of two-photon absorption (TPA). TPA is a problem in its own right because it induces extra waveguide losses at high power. Already at a continuous wave power of a few tens of mW the penalty sets in. Silicon nitride has a weaker Kerr nonlinearity but the TPA is virtually zero in view of the material's large bandgap. Therefore it has been possible to demonstrate frequency comb generation as well as supercontinuum generation in SiN photonic wires [14-17]

Scaling up the silicon-on-insulator (SOI)-based device dimensions in order to extend the operation wavelength to the short mid-infrared (MIR) range (2–4 μm) is attracting research interest, owing to the host of potential applications in lab-on-chip sensors, free space communications, and much more. Other material systems and technology platforms, including silicon-on-silicon nitride, germanium-on-silicon, germanium-on-SOI, germanium-on-silicon nitride, sapphire-on-silicon, SiGe alloy-on-silicon, and aluminum nitride-on-insulator are explored as well in order to realize low-loss waveguide devices for different MIR wavelengths. In pursuit of the optical waveguide with low propagation loss, various platforms and geometric structures were demonstrated. The reported works are summarized in Table1 [18].

No.	Platform	Structure Type	Cross-Section Size (μm×μm)	Working Wavelength (μm)	Loss (dB/cm)	Pol.	Year
1	SOI	Strip	0.9 × 0.22	2.1	0.6	TE	2012
2	SOI	Rib	0.9 × 0.34 (H_{slab} = 0.1)	2	1	TE	2016
3	SOI	Rib	2 × 2 (H_{slab} = 0.8)	3.39	0.6–0.7	TE/TM	2011
4		Rib	2 × 2 (H_{slab} = 0.8)	3.73	1.5 ± 0.2		
5	SOI	Rib	2 × 2 (H_{slab} = 0.8)	3.8	1.8 ± 0.3	TE	2012
6		Strip	1 × 0.5	3.74	4.6 ± 1.1		
7	SOI	Suspended Rib	1 × 0.34 (H_{slab} = 0.1)	2.75	3 ± 0.7	TE	2012
8	SOI	Rib	1.35 × 0.38 (H_{slab} = 0.22)	3.76	5.3	TE	2013
9		Strip	1.35 × 0.4		3.1		
10	SOI	Slot	0.65 × 0.5, (gap = 0.078 μm)	3.8	1.4 ± 0.2	Slot Mode	2015
11	SOI	Strip	4 × 2.3	3-4	<1	TE	2017
12	SOI	Strip	1.2 × 0.4	3.75	2.65 ± 0.08	TE	2017
13		Rib	1.2 × 0.4 (H_{slab} = 0.16)		1.75 ± 0.22		
14	GOS	Strip	2.9 × 2	5.8	2.5	TM	2012
15	GOS	Rib	2.7 × 2.9, (H_{slab} = 1.2)	3.8	0.6	TE	2015
16	GOI	Strip	6.5 × 0.85	3.682	~8	TE/TM	2016
17	GOI	Strip	5.5 × 0.85	3.682	~10	TE/TM	2016
18	GOI	Rib	0.6 × 0.22 (H_{slab} = 0.05)	2	14	TE	2016
19	GOSN	Strip	2 × 1	3.8	3.35 ± 0.5	TE	2016
20	SOSN	Rib	2 × 2 (H_{slab} = 0.8)	3.39	~5 ± 0.6	TE/TM	2013
21	SOS	Strip	1.8 × 0.6	4.5	4.3 ± 0.6	TE	2010
22	SOS	Strip	1 × 0.29	5.18	1.92	TE	2011
23	SGOS	Strip	3.3 × 3	4.5	1	TM	2014
24			7 × 3	7.4	2		

Table1. Demonstrated MIR waveguides with various Platforms [18]

III. Silicon based Optical Devices

3.1 Integrated waveguide PIN photodiodes

Germanium photodetectors are considered to be mature components in the silicon photonics device library. They are critical for applications in sensing, communications, or optical interconnects. In this [19] work, they report on design, fabrication, and experimental demonstration of an integrated waveguide PIN photodiode architecture that calls upon lateral double Silicon/Germanium/Silicon (Si/Ge/Si) heterojunctions. This photodiode configuration takes advantage of the compatibility with contact process steps of silicon modulators, yielding reduced fabrication complexity for transmitters and offering high-performance optical characteristics, viable for high-speed and efficient operation near 1.55 μm wavelengths. More specifically, experimentally obtained at a reverse voltage of 1V a dark current lower than 10 nA, a responsivity higher than 1.1 A/W, and a 3 dB opto-electrical cut-off frequency over 50 GHz. The combined benefits of decreased process complexity and high-performance device operation pave the way towards attractive integration strategies to deploy cost effective photonic transceivers on silicon-on-insulator substrates.

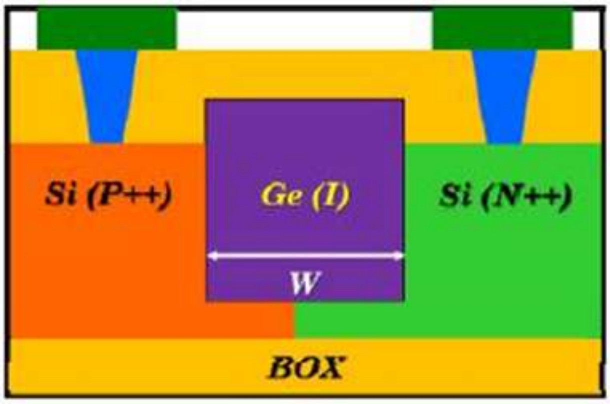


Fig.1 Schematic cross-section of the Ge waveguide PIN photodiode based on the lateral Si/Ge/Si heterojunction. [19]

3.2 Microring –Based Optical Isolator and Circulator

Optical isolators and circulators fabricated by bonding cerium-substituted yttrium iron garnet (Ce:YIG) on silicon microring resonators[20]. A novel integrated electromagnet is fabricated by depositing a metal micro-strip on the bonded chip also experimentally prove that it can be efficiently used to control the magnetic field needed to induce the nonreciprocal phase shift effect in the Ce:YIG. The fabricated devices exhibit extremely small footprint (<70 μm) and can be packaged, eliminating the need of a large size permanent magnet. A large optical isolation of 32 dB and 11 dB is measured for the isolator and the circulator, respectively. Moreover, a two micro-ring solution is also investigated to provide larger bandwidth and higher isolation. This approach represents a promising solution for large-scale integration of nonreciprocal components in silicon photonics.

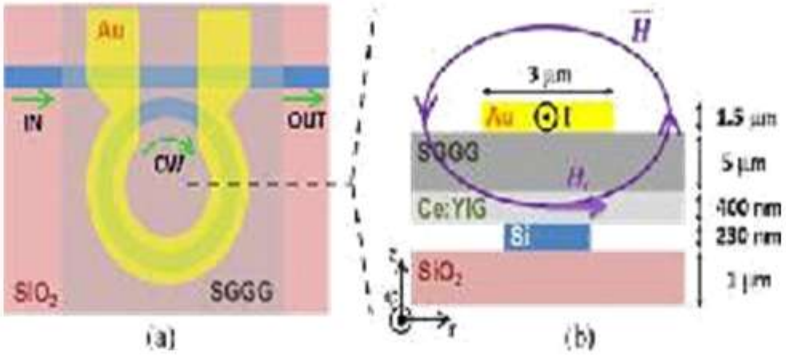
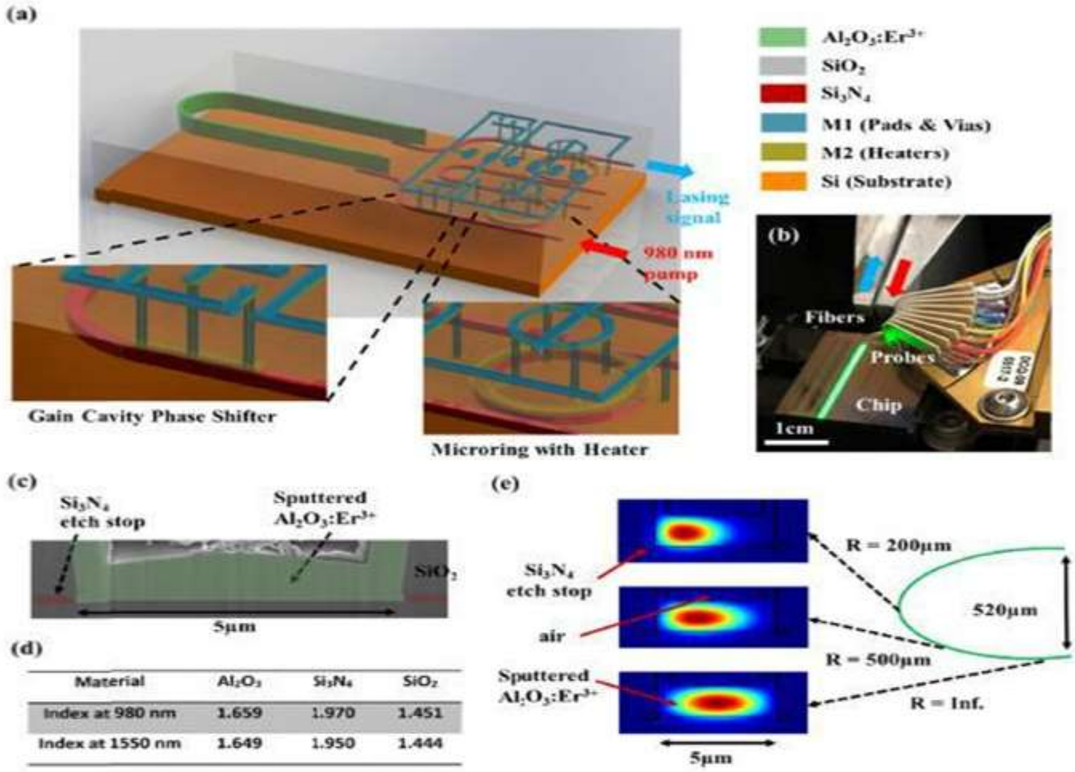


Fig. 2. (a) Top view of the isolator. (b) Cross-section of the microring resonator. The cylindrical coordinate system is shown in (b) as a reference frame. Pictures are not to scale [20]

3.3 Integrated erbium-doped tunable laser

A tunable laser source is a crucial photonic component for many applications, such as spectroscopic measurements, wavelength division multiplexing (WDM), frequency modulated light detection and ranging (LIDAR), and optical coherence tomography (OCT). In this paper [21] demonstrate the first monolithically integrated erbium-doped tunable laser on a complementary-metal-oxide-semiconductor (CMOS) compatible silicon photonics platform. Erbium-doped Al2O3 sputtered on top is used as a gain medium to achieve lasing. The laser achieves a tunability from 1527 nm to 1573 nm, with a >40 dB side mode suppression ratio (SMSR). The wide tuning range (46 nm) is realized with a Vernier cavity, formed by two Si3N4 micro-ring resonators. With 107 mW on-chip 980 nm pump power, up to 1.6 mW output lasing power is obtained with 2.2% slope efficiency. The maximum output power is limited by pump power. Fine tuning of the laser wavelength is demonstrated by using the gain cavity phase shifter. Signal response times are measured to be around 200 µs and 35 µs for the heaters used to tune the Vernier rings and gain cavity longitudinal mode, respectively. The line width of the laser is 340 kHz, measured via a self-delay heterodyne detection method. Furthermore, the laser signal is stabilized by continuous locking to a mode locked laser (MLL) over 4900 seconds with a measured peak-to-peak frequency deviation below 10 Hz



Material	Al_2O_3	Si_3N_4	SiO_2
Index at 980 nm	1.659	1.970	1.451
Index at 1550 nm	1.649	1.950	1.444

Fig. 3(a) 3D illustration of Tunable Laser, showing different material layers, heaters for microring and gain cavity phase shifters (not to scale) (b) Fabricated device on the test set up, showing Erbium green colour fluroscence under 980nm pump (C) SEM image of tunable laser gain waveguide cross section (d) Refractive

indices of waveguide materials at both pump and signal wavelengths. (e) Transverse electric field intensity of the fundamental mode at the signal wavelength for different bend radii along the euler bend [21]

A schematic perspective view of the tunable laser design is shown in Fig. 3(a), which includes all the layers used in the silicon photonics platform. It has a compact footprint of 0.23 cm2 (1 mm × 2.3 cm). Figure 3(a) includes the zoom-in view of the wavelength tuning components, which consists of two microring filters in a Vernier configuration and a gain cavity longitudinal-mode phase shifter with metal heater layer on top.

3.4 Silicon Photonics Optical Transreceiver

Researcher successfully developed a high-density broadband 16-channel × 25 GB/s on-package silicon photonics optical transceiver [22]. The flip chip bonded bridge structure realized high density of about 363 Gb/s/cm2 and also demonstrated simultaneously on all 16 channels error-free operations with low crosstalk penalties of Tx-to-Tx 1.4 dB, Rx-to-Rx 1.4 dB, and Tx-to-Rx <0.1 dB**.** As a structure of the next generation optical TRx, on-package (PKG)-type is thought to be promising. The TRx is placed near large scale integration (LSI) and is co-mounted on a PKG substrate. This is because it is advantageous to overcome the limit of the number of pins on the backside of a PKG substrate [23] and to reduce the consumption of power in order to compensate for the distorted electrical signals such as equalizers by shortening the electrical wiring lengths between the LSI and the TRx. To place several TRxs adjacent to the LSI chip on a limited area of a PKG substrate, a small footprint is an important issue. For realizing such a broadband capability and high-density TRx, silicon photonics technology is suitable. This is because the TRx optical elements are able to be integrated in a photonic integrated circuit (PIC). Furthermore, a PIC, which is made of a silicon substrate, can be assembled on a PKG substrate using conventional electric packaging technologies. Taking all this into consideration, we have developed an on-PKG-type silicon photonics optical TRx with a “high-density bridge structure.” Researchers demonstrated the bridge-assembled 25 GB/s silicon photonics transmitter (Tx) and receiver (Rx) with single-ch operation [24]. Recently, we demonstrated simultaneous 12-ch × 25 GB/s operation with low crosstalk penalty using a prototype of multi-ch silicon photonics Rx [25]. As a next step, researchers worked on the development of an aggregate 400 GB/s broadband and high-density optical TRx for realizing the broadband interconnect. To add 16-ch Tx lanes to develop the receiver, the TRx also requires the performance of low crosstalk penalties of Tx-to-Tx, Tx-to-Rx.

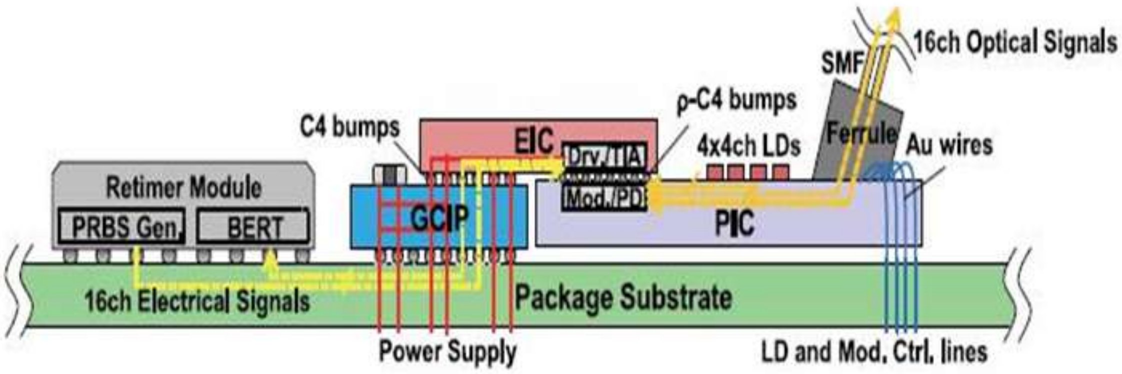


Fig. 4. A schematic structure of 16-ch × 25 Gb/s silicon photonics optical TRx on package substrate. We employed a high-density bridge assembly. Here, the EIC and PIC are bonded by solder bumps and they are mounted on a glass ceramic interposer (GCIP). [22]

Fig. 4 shows a schematic of the structure of the TRx. To realize the multichannel operation, the signal lines and the power lines have to be carefully designed. Researchers employed a high-density bridge structure [26]. In the structure, an electric integrated circuit (EIC) die and a PIC die were flip chip bonded directly by solder bumps. This enabled us to minimize the wiring length and the parasitic capacitance between the electronic and photonic circuits, and to mitigate the degradation of the electrical signals between the trans-impedance amplifiers (TIAs) and photo detectors (PDs), the drivers and modulators, respectively. Researchers also employed a high-density glass ceramic interposer (GCIP) to support the bonded chips on a flat surface of a PKG substrate. The GCIP can accommodate many signal and power lines without many bonding wires connecting the PIC with the PKG substrate. Laser-diode arrays (LDs) were mounted as light sources for Tx and processed multifiber ferrules as optical I/O were fixed on the PIC. Retimer modules were co-mounted on a PKG substrate. The retimer modules functioned as pseudo random bit sequence (PRBS) generators and bit error rate testers (BERTs) to demonstrate simultaneous 16-ch Tx and Rx operation.

As measures for suppressing crosstalk penalties, Researchers designed the signal lines and the power lines as described below. At first, to reduce the reflections and crosstalk interference in the signal lines, they designed 100 Ω differential signal lines even on the EIC and 100 Ω signal vias inside the GCIP. The patterns of signal vias, ground vias, and planes in the GCIP were laid out properly to satisfy the characteristic impedance of 100Ω.Hence, the transmission signal lines of 100 Ω differential signal lines between the retimer modules and TRx elements on the EIC were designed. Next, in order to reduce the simultaneous switching noise (SSN) in the power lines, they ensured the impedance of the power lines for Tx and Rx were lower than target impedances. We set the target impedance for Tx and Rx to 50mΩ and 80mΩ, respectively. Here, we considered the fluctuation ratio of the power at the EIC. In the design, we put capacitors on the GCIP in order to reduce the L-C resonant peaks at 100–200 MHz in the frequency characteristic for the power lines. Furthermore, we laid out 60 nF and 35 nF on-chip-capacitors adjacent to the Tx and the Rx power lines on the EIC, respectively. Finally,we obtained low impedance power lines for Tx and Rx. Then, in order to ensure the Tx power noise did not affect the Rx sensitivity, the power lines for the Tx and the Rx were perfectly separated from the PKG substrate.

IV. Applications and Future aspects

Silicon photonics, extremely powerful technology in the recent trades, fulfils the demands for higher speed, efficiency, and low power consumption at lower costs. In silicon technology, various opto-electronics devices integrate on a single substrate connected with each other using narrow waveguides. Such circuits could be used to establish high speed transmission, increased bandwidth, reduced power consumption and decreasing latency problems. It can potentially increase the bandwidth capacity by providing micro-scale, ultralow power devices. Optical data transmission increases the data rate and eliminates the problem of electromagnetic interference. With these data rates one could imagine the videoconferencing with a high resolution that the actors or family members appear to be in the room with you. Optical link can transfer data over longer distances and faster than today's copper technology; up to 50 GB of data per second. Recently, Intel Corporation launched their optical link connection operating 100Gbps [27]. Fujitsu Laboratories recently developed four wavelength integrated silicon laser for optical transrecievers. Work is in the progress for the new optic-interconnection of external devices to PCs. Intel introduced Light Peak, 2009 which replaces the USB and communicates the data at up to 10Gbps. Researchers Advancement in the field of silicon nanophotonic technologies leads new ideas in future computing systems and their architectures. Researchers have successfully developed silicon optical devices such as integrated waveguide PIN diodes, Microring –Based Optical Isolator and Circulator, Integrated erbium-doped tunable laser and Silicon Photonics Optical Transreceiver with excellent performance than existing devices.

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