High Speed Silicon Modulators

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Abstract
Recent silicon modulator research using ring modulators, electroabsorption modulators, and Mach-Zehnder modulators are reviewed and compared for specific applications.

Introduction
The emerging research conducted on silicon photonics has emphasized its potential to utilize low cost, mature and mass productive CMOS processes. The goal of integrating photonics together with electronic devices has become one of the major possibilities to provide higher capacity for future computation. Among all of the silicon photonics devices, the silicon modulator is one of the important components in optical communication network. Due to the lack of efficient electro-opto (EO) effect in silicon, research on different structures is under investigation to deliver potential solutions and applications. Discussion of the fundamental operation principle, performance, and application for each structure will be summarized in this paper.

Micro-ring modulator (RM)
Micro-ring modulators have been widely explored due to its ultra compact footprint and low drive voltage. The micro-ring has a nature resonant frequency based on the device dimension. By introducing an index change inside the ring, the resonant frequency can be shifted and thus a large modulation depth occurs near the resonance. A micro-ring modulator utilizing carrier injection was demonstrated recently [1]. The radius of such a ring modulator can be as small as 5 μm with only 1.8 V voltage difference acquired to shift the resonant frequency and results in a 17 dB extinction ratio (ER). The device is well known for its extremely compactness and sharp modulation; applications such as comb generator, comb switch, and optical filter are also demonstrated based on the mirco-ring structure [2,3]. However, due to the nature of ring structure, the optical bandwidth of the ring modulator is generally smaller than 1 nm so that cascaded rings or more complicated structure is needed for a multi-wavelength system. Moreover, the device is also very sensitive to environment temperature, bias condition, and fabrication variations. Any error can result in the resonant shift, hence extra components such as thermal heaters are usually applied for tuning purpose.

As for high speed communication, the reported micro-ring resonator has a large signal modulation at 12.5 Gb/s with 9 dB ER. However, this can only be achieved by utilizing a pre-emphasized electrical driven signal (V_{pp} = 8 V plus 3.5 V pre-emphasized pulse) since carrier injection is a relatively slow process limited by nanosecond carrier lifetime. It is possible to increase the modulation bandwidth if carrier depletion is used to introduce the phase change. Nevertheless, either the size of the ring or the overlap between optical mode and carrier swept region has to be increase because carrier depletion is a weaker effect than carrier injection to introduce the index shift.

Electroabsorption Modulator (EAM)
Electroabsorption modulator has been a very common device used in optical communication on the pure III-V platform over the past decade. By applying bias on the material, the bandgap can be manipulated, and thus results in red shift of absorption spectrum. Silicon, however, is well known as an indirect bandgap material and the absorption efficiency is fairly weak compared to III-V material. Therefore, two different approaches, Germanium (Ge) grown on silicon and III-V bonded to silicon, have been used to solve this problem. The SiGe EAM based on the Franz-Keldysh and quantum confined Stark effects was reported recently [4,5]. The waveguide SiGe EAM demonstrated in [4] has small footprint around 50 μm in length and low energy consumption per bit. However the absorption coefficient in SiGe multiple quantum wells (MQW) is still lower than InP MQW. The additional absorption caused by indirect bandgap of Ge also introduces higher propagation loss at zero bias as shown in Table 1.
Another approach is to fabricate the EAM on the hybrid silicon evanescent platform [6], which consists of III-V material bonded with patterned silicon on insulator (SOI) wafers such that the active devices can be implemented using III-V material property while low loss waveguide can be made on SOI. The hybrid silicon EAM has 10 dB ER at -5 V and only 3.6 dB/mm propagation loss at zero bias. Moreover, it has not only a large modulation bandwidth of 16 GHz but also large signal modulation with 11 dB ER at 10 Gb/s. The large ER at high speed is necessary and important for practical application in the optical communication networks.

	Ring Modulator	EAM		MZM			
Group	Cornell	UCSB	MIT	UCSB	Intel	IBM	IEF
Platform	Si	Hybrid Si	SiGe	Hybrid Si	Si	Si	Si
ER (dB) and driven bias (V_{pp})	17 (1.8 V)	10 (5 V)	10 (7 V)	12 (4V)	>20 (6V)	6 to 10 (1.8V)	14 (10V)
Bandwidth (GHz)	—	16.0	1.0	8.0	20.0	—	8.0
ER(dB) at high freq.(Gb/s)	9dB at 12.5G*	11dB at 10G	—	6.38 at 10G	1dB at 30Gb	? at 10G*	—
Optical bandwidth (nm)	<1	30	15	> 100	> 75 nm	—	> 30 nm
$V_{\pi}L$ (Vmm)	—	—	—	2	40	0.36	50
length (um)	10	100	50	500	1000	100	4000
loss(dB)/device	—	3	14.8	3	5.4	12	5

Table 1. Comparison of silicon modulators. Data are taken from ref. [1-10]

Mach-Zehnder Modulator (MZM)

The third option is the Mach-Zehnder interferometer (MZI). By changing the phase on one or both arms of the MZI, either constructive or deconstructive interference is achieved, and consequently intensity modulation can be expected. In order to introduce π phase shift, EO effects, such as carrier injection or carrier depletion, are generally used. The device footprint is generally around millimeter scale due to the weak EO effect inside silicon [7-8]. High speed silicon modulator using carrier depletion effect with 1 dB ER at 40 Gb/s and $V_{\pi}L = 40$ V-mm was reported in [7]. In contrast the silicon MZM based on forward bias carrier injection can lead to a small footprint (100 μm), yet has a carrier lifetime limited bandwidth[9]. Although large modulation of 10 Gb/s was demonstrated by using pre-emphasized electrical driven signal, extra RF power is required. In order to overcome the tradeoff between the modulation efficiency and high speed operation, hybrid silicon MZMs were demonstrated to have moderate $V_{\pi}L = 2$ V-mm, and 10 Gb/s large signal modulation, not limited by intrinsic material properties [10]. High speed operation up to 40 Gb/s is expected for such a hybrid MZM if a traveling wave electrode is utilized.

Comparison

In order to compare different types of modulators, Table 1 lists some of the important parameters for each specific modulator. As can be seen, the ring modulator is compact and operating at sub-voltage, but the optical and modulation bandwidth are both limited. It is suitable for high density and narrow bandwidth applications. In contrast, the EAM has slightly larger footprint, decent modulation efficiency and high modulation bandwidth up to 16 GHz. For reconfigurable communication system which require larger optical bandwidth, the EAM is a good candidate. The MZM has a larger footprint and requires higher bias condition; however, it has a wider optical bandwidth, higher large signal modulation, and potential applications such as switches and routers make it very competitive for future all optical communication networks.

Conclusions

Recent process on silicon modulators has been reviewed and summarized in this paper. Future development is expected in the next few years with better modulation efficiency, higher optical and modulation bandwidth. This research is promising for future optical interconnects using silicon photonics.

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