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Microring-based Electronic-Photonic Integrated Circuits

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Silicon photonics is a promising solution to meet the increasing bandwidth demands in future terabit-per-second data communications. It takes advantages of the ultrawide optical bandwidth and ultrafast transmission speed of photonics, while at the same time inherits the existing manufacturing infrastructures from microelectronics industry. Silicon photonics is advancing rapidly in recent years, highlighted by various high performance passive and active silicon photonic devices, including low loss silicon waveguides, fiber couplers, multiplexers/demultiplexers, modulators, Ge-on-Si photodetectors, and silicon lasers. As all the necessary building blocks are individually realized on the silicon platform, the next challenge will naturally be the integration of photonic devices with electronic circuits in a single silicon chip.

As previously demonstrated on the III-V semiconductor-based photonic integrated circuits (PICs), electronic-photonic integration is challenging both in physical device fabrication as well as in system and circuitry design. The device fabrication challenges lie in the development of a low-cost CMOS-compatible process that effectively integrates photonics within the limitations posed by CMOS electronics, e.g. temperature envelops. On the system and circuit design side, electronic-photonic integrated circuits (EPICs) need to address the fundamental mismatch between the large potential bandwidth of photonics and the significantly lower speed of CMOS electronics.

To overcome this challenge, many previous works use wavelength-division multiplexing (WDM) in order to split the optical bandwidth in the wavelength domain to achieve a larger aggregated data rate. For example, Intel has demonstrated a new 50-Gbps silicon photonics link last year based on four-wavelength multiplexing. However, on-chip WDM systems are usually complicate to design and difficult to implement, including the issues of channel cross-talk, integration of a large number of source-detector pair, clock synchronization between multiple sources, etc.

We propose to time-share the optical bandwidth by applying time-interleaving circuit techniques in photonics. Time-interleaving schemes have been widely employed in high-speed electronics, which increases the overall bandwidth of the system by incorporating several low-speed subsystems in parallel and operating them in sequence. Applying time-interleaving techniques in high-speed EPICs would effectively relax the bandwidth requirement in each subsystem, and hence the relatively low-speed electronics can be used to achieve the large bandwidth enabled by the photonics.

As an example of utilizing time-interleaving technique in silicon photonics, this thesis presents a new EPIC concept based on microrings. In addition to their wavelength- domain properties as add-drop filters, the time-domain properties of microrings are explored. In this new microring-based optical pulse train generator (M-OPTG), multiple stages are coupled in series to the input waveguide, and each stage is composed of microring add-drop filters. All the stages resonate at the same wavelength, which is shifted from the input wavelength by design. They are used as compact couplers to equally divide the input pulse energy. When an input trigger pulse is launched and propagating through the input waveguide, its pulse energy is partially coupled to all the stages. After that, the time-interleaved stage outputs are combined to form an optical pulse train at the circuit output. The circuit can be used for optical arbitrary waveform generation (OAWG) by controlling the amplitude and timing of the output pulses. It can also be easily developed into an ultrafast optical transmitter by actively modulating the microrings.

As a methodology, transfer matrix method combined with full-wave electromagnetic (EM) simulation is developed to analyze large microring-based EPIC systems. The EM simulation is first conducted to obtain accurate numerical parameters of the photonic devices, and then the transfer matrix method is applied for the system level analysis. A four-stage M-OPTG prototype is designed and fabricated on a silicon-on-insulator (SOI) substrate using e-beam lithography. Four identical pulses that are 50-ps apart duplicate the 10-ps-wide input pulse at the output, indicating a high pulse repetition rate of 20 GHz. The preliminary experimental results verify the multiply-by-4 circuit function, with pulse repetition rates of 18 GHz and 33 GHz demonstrated by two prototypes respectively.

To fully utilize the filter function of microrings as well as time-interleaving circuit technique to boost the repetition rate of the input pulse train, WDM and time-domain multiplexing (TDM) are combined in a new multi-wavelength M-OPTG concept. Dif- ferent from the single-wavelength design, microrings in all the stages resonate at dif- ferent wavelengths, and are used as WDM multiplexers to filter the wideband input spectrum and multiplex it to the output. Moreover, since all the stage outputs have different wavelengths, they can be combined with a single output waveguide with no “back-coupling” problem. This removes the power loss introduced by the “asyn- chronous” optical combining at the circuit output in the previous single-wavelength design. A design of a 30-wavelength M-OPTG impressively demonstrates this circuit concept by multiplying the input repetition rate 30 times at the output, which can be used as a guideline for the future implementation of the circuit.

A four-wavelength prototype is fabricated on SOI as an experimental demonstration of the multi-wavelength M-OPTG. To solve the microring resonant wavelength shift problem, Ti/Au heaters are implemented on top of the microrings to thermally control their resonant wavelengths. Applying thermal tuning, the output waveform of the prototype shows four identical pulses with a pulse width of 25 ps and a timing delay of 60 ps between the adjacent pulses. The total power consumption for the thermal tuning is about 13.75 mW . The pulse repetition rate is demonstrated to be 17 GHz.