Photonics-Enabled Innovations in RF Engineering

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***Abstract*— We review the recent research outputs at Monash Electro-Photonics Laboratory in the field of microwave photonics, where the latest advances of photonic technologies are applied for new innovations in RF engineering.**

Keywords—Microwave photonics; integrated optics; photonic integrated circuit; silicon photonics; silicon modulator.

I. INTRODUCTION

Microwave photonics opens an alternative path for RF engineering where the advantages of photonics such as THz bandwidth, multi-octave tuning mechanism, reduced electromagnetic interference, and easy incorporation of fiber transmissions are leveraged to enable features and functions that are challenging to realize with conventional RF engineering solutions that use only electronics [1]. These added merits stimulate new innovations in modern RF technologies, e.g. RF filters with DSP-like flexibility [2], K_u-band beamformers [3] with continuously tunable delay lines [4], low-power ADCs/DACs [5], and multi-GHz switches [6].

One key research activity of the Electro-Photonics Laboratory at Monash University (MEPL) is to consider new innovations in RF engineering using the latest advances of photonic technologies, with particular strength for solutions using hybrid electrical-photonic signal processing and photonic integrated circuits (PICs) [7]. Figure 1 shows a diagram of the general approach for providing microwave photonic solutions and snapshots of the capabilities at MEPL.

II. REPRESENTATIVE WORKS

A. Photonics-assisted DACs

Conventional approaches for generating modulated electrical waveforms often include power-hungry FPGAs, DACs and driver amplifiers. We proposed designs of optical modulators that do not require DACs. One simple method is to use a counter-propagating modulator [5]. Here the optical signal is fed into the opposite end of a commercial phase modulator to the electrical signal. The optical phase change is then a finite-duration integral of the electrical waveform. This means that a pulse-width-modulated electrical waveform is converted to an analog phase change, which can then be converted to an optical intensity variation using a Mach-Zehnder interferometer.

B. Photonic Wadley Loop

The Wadley Loop is a well-known technique to stabilize the local oscillator (LO) in the radio receivers by combining the stability of a single crystal with the wide tunability of a LO. This technique can also be applied to coherent optical systems to create a widely-tunable LO laser with a narrow linewidth. In our demonstration, we combined the stability of a mode-locked laser with a widely-tunable laser in an electro-optical system, using multiple mixing processes [8]. This means that the variable-frequency outputs of multiple tunable lasers can be quantized to the comb-spectrum of a single mode-locked laser as a master oscillator for networks.

C. Optical pulse manipulations for photonic ADC

Electrical clock recovery that relies on a phase detector locks a clock to a data stream. We have demonstrated an electro-optical equivalent of this function, i.e. a delay discriminator, which compares the timing of optical signal pulses to local optical clock pulses [9]. We counter-propagate two pulse trains within an semiconductor optical amplifier (SOA) where the first pulse to enter the amplifier gets the most gain and the second pulse sees the depleted gain due to the first pulse. Thus by measuring the relative intensities of the output pulse trains on a long timescale, their relative timing can be determined. Implemented using a dedicated indium phosphide PIC that comprises a cascade of three SOAs as shown in Fig. 1d, we have demonstrated the timing detection of GHz-rate optical pulses with kHz-rate electrical output.

Sampling in the optical domain is another useful function for the receiver. It enables the time-domain demultiplexing of OTDM channels and can also be employed to reduce the

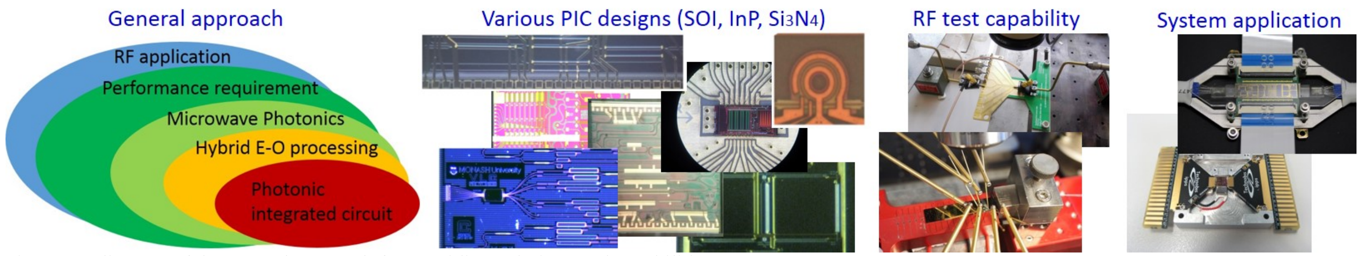

Fig. 1. A diagram of the general approach for providing solutions and capabilities at MEPL.

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receiver electronic bandwidth requirement for Nyquist WDM and OFDM systems. Our implementation of an optical sampler is an indium phosphide PIC comprising a SOA incorporated in a Sagnac loop [10]. The nonlinear property of the SOA converts the intensity variation of a period optical pulse train as control signal to phase variation of the light carrying data signal. In the Sagnac loop, the clockwise-travelling and counter-clockwise-travelling lights receive different amount of phase variations, depending on their interaction time with the control signal in the SOA. Eventually, by means of interference, the output coupler of the Sagnac loop translates this phase variation difference into an amplitude time gate that performs the sampling. While this concept has been well discussed, the implementation on a very compact optical chip points out the possibility of integrating the optical sampler function into the receiver as one device.

D. Multi-GHz RF switches

One important RF area that photonics promises to make an impact on is high-speed RF switches, where switching frequencies in the order of multiple GHz is challenging to implement using the conventional all-electronic approaches. In microwave photonics, several previous proposals using discrete components have demonstrated the functions of amplitude, phase, and frequency switching at speeds up to tens of picoseconds, i.e. tens of GHz [6]. However, just like RF industry, the commercial adoption of microwave photonics solutions requires device down-sizing and integration. In addition, functional reconfigurability is also a desirable feature to facilitate new innovations of flexible systems. Recently, we demonstrated a photonic implementation of a multi-GHz RF phase switches using a silicon microring modulator, and its application for the generation of binary-phase-coded waveforms at 40 GHz. It is not only able to perform switching at high speeds, but also doubling of the seed RF frequency.

E. Shape-reconfigurable RF filter

Regarding RF filters, the filter shape reconfigurability is a desirable feature, as it significantly broadens their potential for applications. Besides, having an entire filter integrated on a chip provides the ultimate system stability, control precision, and device compactness. Recently, we demonstrated a highly reconfigurable photonic RF filter implemented using a serial cascade of three of silicon nitride ring resonators [2]. In the experimental demonstration, DSB modulation is employed, which can be easily implemented using an intensity or phase modulator. A pair of identical ring resonators are used for filter shape synthesis and a third ring resonator with a smaller size is used to perform the function as modulation transformer [11] that enables a separate manipulation of the phase of the optical carrier. After detection, a RF filter with a nearly DSP-level of shape reconfigurability is implemented, with all the reconfiguration operations performed on chip.

F. Programmable optical chips

To date most optical chips are fabricated using the so-called application-specific photonic integrated circuits, in which a particular circuit and chip configuration are designed to perform a specific function. This paradigm for device realization is in general expensive and time-consuming. In contrast, we have proposed a radically different approach, i.e. a general-purpose signal processor chip that is able to perform different functions via software programming. Our design is inspired by electronic FPGAs and uses a 2D lattice mesh network of Mach-Zehnder couplers [12]. We have proven this concept experimentally using a chip with two mesh cells.

III. CONCLUSION

Utilizing the advantages of photonics, microwave photonics enables unprecedented features of RF functions with respect to signal bandwidth and frequency, system parameter tunability, electromagnetic interference reduction, and potential improvement for cost and power efficiency. These features inspire new innovations in RF engineering, promising upgrade of exiting functions and creation of new ones in RF technology. PICs are a key hardware platform technology to realize photonic sub-systems on the chip scale, providing the practical device features of small size and weight, precise control, robustness, and potential for low-cost fabrication in volumes. We anticipate integrated microwave photonic solutions to thrive in the near future with the drive of high-bandwidth RF applications such as 5G wireless communications, satellite communications, high-resolution radars, sensor networks, and radio astronomy.

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