Electro-photonics for high-capacity and energy-efficient optical communication networks

(Invited)

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Abstract—**We review the recent research outputs at Monash Electro-Photonics Laboratory in a new field: electro-photonics, where the best of the electronic and photonic technologies are combined to increase the capacity, flexibility and energy efficiency of optical communications systems and networks.**

Keywords-optical fiber communications networks; optical signal processing; optoelectronics; photonic integrated circuits.

I. INTRODUCTION

CISCO^{TM} has forecasted that the annual global IP traffic will reach 2.3 zettabytes by 2020 [1], which is a factor of three increase compared with now. With this ever- and fast-growing traffic, new challenges in capacity, flexibility, and energy efficiency have been raised for the optical communications network technologies. While optical fibers are potentially able to support much higher transmission line rate, a further advance of network devices performing signal processing such as transmitters, receivers, and switches is needed to further exploit this potential of optical fibers and address those challenges for the network technologies.

Currently, electronic digital signal processing (DSP) might be dismissed as being too slow to support high data rates and too hungry in power consumption, while optical signal processing might be dismissed as being inflexible. The truth is that both electronic and photonic technologies are advancing rapidly. At any particular instant, there will be a different optimal mix of these technologies. This mix will also be influenced by non-technological factors—for example, digital signal processing for dispersion compensation eliminates the need for back-room engineering to plan the dispersion maps of long-haul links, so overcomes a labor shortage.

The aim of the Electro-Photonics Laboratory at Monash University, Australia, is to consider the best mix of optical and electronic technologies to produce an optimal solution for a particular problem, where a new science of electro-photonic circuits is developed to transform the processing of optical signals in the internet [2]. Figure 1 shows a unified conceptual framework for hybrid photonic and electronic signal processing, incorporating energy-consumption models, to allow processing tasks to be optimally shared by a combination for electronic and photonic processing.

II. REPRESENTATIVE WORKS

A. *All-optical signal generation (OFDM/N-WDM)*

The concept of 'universal' transmitters allows the signals to be generated with their spectra and central wavelength defined in an all-optical approach, by means of shaping optical pulses using an optical processor [3]. One feasible implementation is to modulate pulses from a mode-lock laser with one or more modulators and perform the spectrum-shaping using a Waveshaper^{TM} [4]. While the Waveshaper provides flexibility, chip-scale optical signal processors using photonic integrated circuits (PICs) are a promising approach for creating multi-wavelength transmitters, offering advantages of small size, weight, and power consumption (SWaP) and potential for low cost in volume production. We have demonstrated that arrayed waveguide grating routers (AWGRs) can be designed as inverse/forward optical Fourier transforms, and so are the basis of all-optical OFDM transmitters and receivers [5]. A design of such a transmitter and an OFDM demultiplexer in silicon are shown in Fig. 1b. We have also shown that a ring resonator-assisted Mach-Zehnder interferometer (RAMZI) fabricated in silicon nitride provides near-Nyquist-bandwidth filtering with very sharp roll-offs as shown in Fig. 1c, while featuring very low circuit complexity and easy control [6]. We have shown that such a device can also be used to upgrade the spectral efficiencies of wavelength-selective switches (ROADMs) [7].

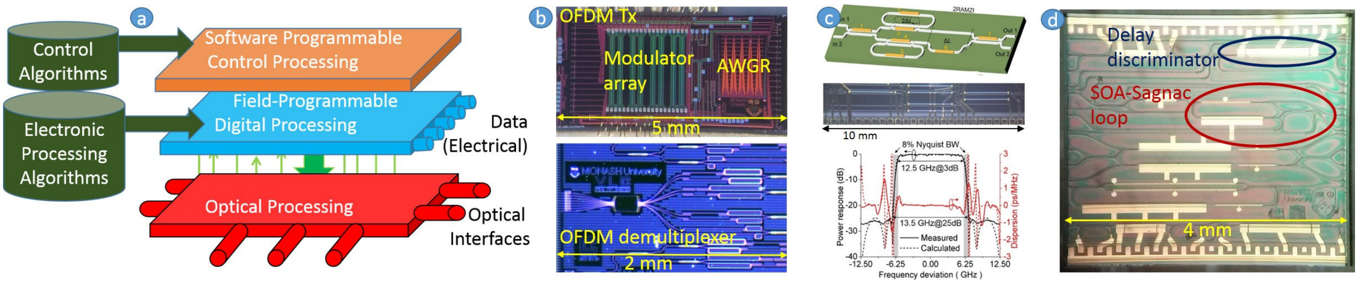

Fig. 1. (a) Concept of hybrid photonic and electronic signal processing. Photomicrographs of (b) an OFDM transmitter and demultiplexer in silicon, (c) a RAMZI in silicon nitride, and (d) a delay discriminator and a SOA-Sagnac loop in InP.

B. Digitally-driven modulators

In modern high-capacity transmission systems, various modulation formats associated with unique electrical waveforms are used, the implementation of which often include power-hungry FPGAs, Digital-to-Analog Converters (DACs) and driver amplifiers. We are working on designs of optical modulators that do not require DACs. One simple method is to use a counter-propagating modulator [8]. Here the optical signal is fed into the opposite end of a LiNbO3 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 (MZI).

C. Optical implementation of eletronic sub-systems

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 [9]. This means that the variable-frequency outputs of multiple tunable lasers can be quantized to the comb-spectrum of a single mode-locked laser, which could be the master oscillator for a while exchange, or indeed, network.

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 incoming optical pulses to locally generated clock pulses [10]. We counter-propagate optical pulses 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 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 [11]. 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. Programmable optical chips

To date most optical chips are fabricated using the so-called application-specific photonic integrated circuits (ASPICs), 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 field-programmable gate arrays (FPGAs) and uses a 2D lattice mesh network of Mach-Zehnder couplers [12]. We have proven this concept experimentally using a chip that comprises two mesh cells, while with limited functions. A further development of this concept with larger network scales and different mesh geometries is expected in the near future.

III. CONCLUSION

Electro-photonics benefits from considering combinations of photonic and electronic technologies to address current problems in generating, processing and receiving high-rate data communications channels. PICs are a key technology to reduce device size, weight and power consumption. We anticipate chip-scale realizations of complex signal processing functions serving for high-capacity and energy-efficient optical communications networks.

REFERENCES

[1] www.cisco.com

[2] www.ecse.monash.edu.au/staff/lowery/

[3] J. B. Schroder, L. B. Du, M. M. Morshed, B. Eggleton, and A. J. Lowery, “Colorless flexible signal generator for elasitc networks and rapid prototyping,” in proc. OFC Anaheim, 2013, p.JW2A.44.

[4] A. J. Lowery, J. Schroder, and L. B. Du, “Flexible all-optical frequency allocation of OFDM subcarriers,” Opt. Express 22, 1045, 2014.

[5] A. J. Lowery, “Design of arrayed-waveguide grating routers for use as optical OFDM demultiplexers,” Opt. Express 18, 14129, 2010.

[6] L. Zhuang et al., “Nyquist-filtering (de)multiplexer using a ring resonator assisted interferometer circuit,” J. Lightwave Technol. 33, 1732, 2016.

[7] L. Zhuang et al., “Sub-GHz-resolution C-band Nyquist-filtering interleaver on a high-index-contrast photonic integrated circuit,” Opt. Express 24, 1732, 2016.

[8] A. J. Lowery, “All-optical DAC using counter-propagating optical and electrical pulses in a Mach-Zehnder modulator,” Opt. Express 22, 26429, 2014.

[9] A. J. Lowery, B. Corcoran, and C. Zhu, “Widely-tunable low-phase-noise coherent receiver using an optical Wadley loop,” Opt. Express 23, 19891, 2015.

[10] A. J. Lowery and L. Zhuang, “Photonic integrated circuit as a picosecond pulse timing discriminator,” Opt. Express 24, 8776, 2016.

[11] L. Zhuang et al., “On-chip optical samling using an integratred SOA-based nonlinear optical loop mirror,” in Proc. ECOC 2016, Dusseldolf.

[12] L. Zhuang et al., “Programmable optical signal processor chip for radio frequency applications,” Optica 2, 856, 2015.

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