General purpose signal processor on an optical chip

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***Abstract*—Integrated optical signal processors have many applications in photonic processing of microwave signals. They provides wideband and stable signal processing operations on miniaturized chips with ultimate control precision. Creating general-purpose processors by introducing programmability is a key to enable system function flexibility and therewith offer great potential for a wide range of applications. Here, we review the recent progress in this area with highlights of a number of key programmable chips and their promising applications.**

***Keywords*— Integrated microwave photonics, analog signal processing, photonic integrated circuit, RF filter**

I. INTRODUCTION

Optical signal processing associated with intrinsic bandwidth and tunability advantages of optics serves as the core in microwave photonic systems that provide RF signal processing functions with as good features [1]. Implementing optical signal processing on photonic integrated circuits (PICs) [2–7] yields the so-called processing core chips with coveted practical features of miniaturized size, long-term stability, ultimate control precision, reduced power consumption, and potential for low cost.

To date, a number of waveguide materials have been investigated for PICs including silicon materials [2–6], III-V semiconductors [7], $LiNbO_3$ [8], polymers [9], chalcogenide glass [10], and plasmonics [11]. Either in sole or combined use, these materials, each with unique features, have enabled a wide diversity of passive and active functions, utilizing both linear and nonlinear optical properties. Some frequently-shown examples include couplers, filters, (de)multiplexers, delay lines, lasers, amplifiers, modulators, detectors, phase conjugators, and wavelength convertors [1–7]. Although showing a great engineering freedom, implementing RF signal processing functions in microwave photonics may require a complex optical system that comprises a combination of many of these functions. In a broad sense, integrating such systems on monolithic chips or by means of chip-level micro-assembly are a key for the proliferation of their applications which address the issues of device size, power consumption, and performance stability simultaneously, as compared with the conventional all-electronics solutions. Serving this purpose, recent rapid advances of high-index-contrast waveguides, i.e. silicon-on-insulator (SOI), silicon nitride (Si_3N_4), and indium phosphide (InP), have successfully yielded many functions as standard building blocks for creating compact high-performance PICs and therewith facilitates the establishment of powerful optical device hardware platforms. Besides, the current fabrication maturity enables large-scale integration of thousands of these functions with high performance uniformity and repeatability [3]. In practice, the generic foundry and multi-project-wafer-run business mode [7] allow both industry and academia to have easy access to high-end fabrication facilities and well-developed building blocks, rendering fast thriving of PIC technology and applications.

Beside their potential for frequency-critical applications for defense and space industries [10], a short-term driver for microwave photonics is wideband wireless communication for the consumer market; e.g. next generation 5G systems, where low-cost and flexible front-end analog processing is desirable [12]. Here, a rational incentive of creating optical processing core chips is the imminent need of a new generation signal processing capability featuring simultaneously large bandwidth, great flexibility, and high power- as well as cost-efficiency, in order to accommodate the rapid and incessant increase of demand for data traffic [12]. Although with high industrial maturity, all-electronics solutions, despite the technology challenges and limitations, are yet too expensive, and power-hungry to facilitate systems with instantaneous bandwidths of multiple gigahertz or greater, particularly for the large-volume, high-carrier-frequency scenarios; e.g. 60-GHz or W-band systems. In contrast, optical processing core chips open a possibility of offering those features all at once.

The current designs of chips are mostly application-specific; that is, they are Application-Specific Photonic Integrated Circuits (ASPICs). From a practical perspective, a programmable chip serving many applications and markets, and supporting post-deployment functional changes, would be desirable. Such chips would also support rapid prototyping, and eliminate the risks and delays inherent in designing ASPICs. In microelectronics, this concept has been validated by the success of signal processors such as field programmable gate arrays (FPGAs), which are a countermeasure to Application-Specific Integrated Circuits (ASICs). Therefore, we believe that creating general-purpose optical processing core chips [13–15] by introducing programmability in PICs opens a path to transfer the inestimable function-enabling power of FPGAs to the field of integrated optics, and will simultaneously give rise to a significant advance of microwave photonic solutions by

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providing a highly time-efficient path for implementing various functions in PICs.

Here, we review an implementation of programmability on an optical chip, and revisit a microwave photonic demonstration of a reconfigurable RF filter using an optical processing core chip fabricated in a commercial TriPleX^{TM} Si$_3$N$_4$ waveguide [4, 6]. Finally, we give an outlook of this study with discussions of possibilities as well as challenges that should be addressed for the ultimate goal of bringing general-purpose optical signal processor chips into deployable products in the future.

II. SIGNAL PROCESSORS IN MICROWAVE PHOTONICS

A. *Processing core chip design*

To date, a large number of on-chip microwave photonic demonstrations of RF signal processing functions have been reported, including splitter, hybrid coupler, spectral filter, phase shifter, differentiator, integrator, Hilbert transformer, frequency discriminator, modulation transformer, frequency convertor, UWB pulse shaper, arbitrary waveform generator, tunable delay line, and beamformer for phased array antennas [1, 6, 10, 16, 17]. A number of works utilizing the nonlinear optical properties such as stimulated Brillouin scattering and four-wave mixing have shown unique features of RF operation bandwidth and frequency resolution [10, 18, 19]. However, the on-chip implementations of these require particular waveguide materials and external off-chip control mechanisms, the practicality of which relies strongly on an advance of photonic integration technology that enables hybrid integration of different waveguide materials while maintaining high performance of each. In contrast, on-chip processing using linear interferometric filters [20] features high transparency to different waveguide platforms and allows for easy implementation of on-chip control as well as integration of multiple functional building blocks to enable complex systems on a chip. The great design freedom of interferometric filters allow for synthesis of arbitrary amplitude and phase responses. In terms of impulse response characteristics, such filters can be divided into two kinds, i.e. finite impulse response (FIR) filters and infinite impulse response (IIR) filters. Their design process is interchangeable with that of digital filters, and therefore benefits greatly from the well-developed digital signal processing algorithms.

For the on-chip implementation, FIR and IIR filters are typically constructed using tapped delay line and ring resonator topologies, respectively, with both kinds comprising a combination of couplers and delay lines. This implies that when a PIC comprises a 2-dimensional lattice mesh network of basic building blocks and each basic building block can be varied to perform either a coupler or a delay line, one can then in principle implement multiple and arbitrary FIR and IIR filter topologies by simply programming those basic building blocks, assuming that the lattice mesh network has a sufficient size. Moreover, when those basic building blocks also allows for amplitude and phase control, one can implement variations of filter shape and frequency. Figure 1a shows a conceptual design of such a mesh network [15], where the square lattice is used for the mesh geometry. The basic building block comprises a Mach-Zehnder interferometer (MZI) coupler whose coupling coefficient and overall phase shift can in principle change in the range from 0 to 1 and from 0 to 2π, respectively, by controlling the phase shifts on both arms [6]. This tuning mechanism of the MZI coupler facilitates the full programmability of the lattice mesh network. In a further study of the mesh geometry [21], Pérez et al. made a thorough comparison between the triangular, square, and hexagonal lattices, and found that the hexagonal mesh is the most suitable option for implementation in terms of circuit complexity and fabrication challenges although the square mesh offers highest routing flexibility of optical paths. Figure 1b shows a schematic and a photograph of a test chip

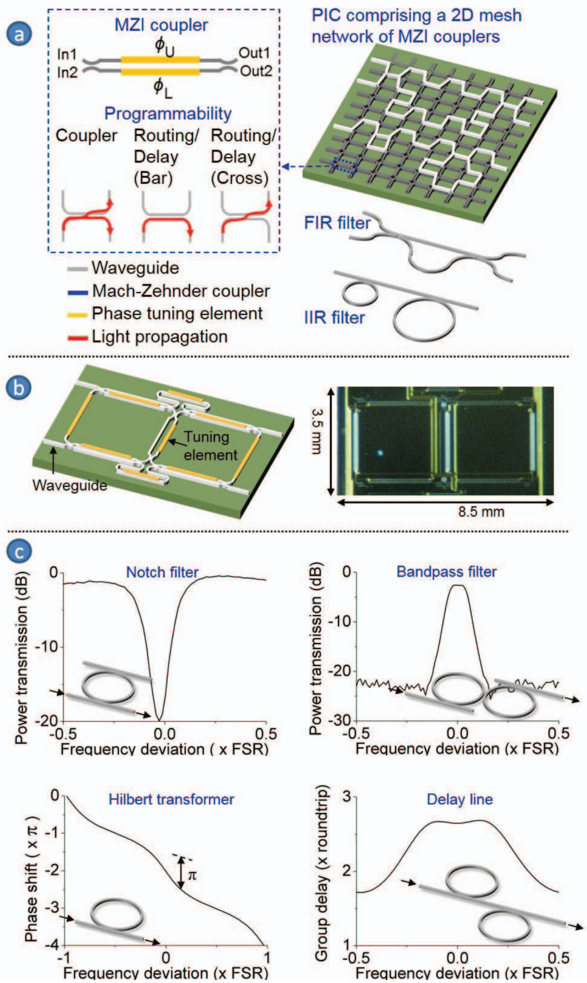

Fig. 1. (a) A conceptual drawing of the PIC topology of a programmable processing core chip. (b) An schematic and a photograph of a test chip comprising a 2 × 1 mesh network (fabricated in the TriPleX^{TM} Si$_3$N$_4$ technology). (c) Experimental demonstration of the programmability of the chip where the chip was programmed to function as a notch filter, a bandpass filter, a Hilbert transformer, and a delay line, respectively.

comprising a 2 × 1 mesh network. The chip is fabricated using a TriPleX^{TM} Si_3N_4 waveguide and uses electrical resistor-based heaters as phase tuning elements [6]. Figure 1c shows measured frequency responses of four different functions (not limited) that the chip is able to perform by programming the two mesh cells into a one-coupler ring resonator, a two-coupler ring resonator, a serial cascade of two independent ring resonators, or a pair of mutually-coupled ring resonators.

B. *Implementations of reconfigurable RF filters*

A typical way to implement a RF filter in microwave photonics is to modify the amplitude and phase characteristics of the RF spectrum in the optical domain. The most straightforward approach is to generate a full-carrier single-sideband (SSB) modulation spectrum and then pass it through an optical filter such that after detection the optical filter shape is copied to the RF domain. Although it is easy to synthesize an optical filter with bandstop shapes, this approach requires complex designs of an optical filter for implementing RF bandpass shapes as the optical filter should suppress the out-of-band frequencies and yet preserve the optical carrier simultaneously to maximize the detected RF power, besides the SSB modulation losses half of the RF power intrinsically. In [15], we demonstrated an approach to implement both RF bandstop and bandpass shapes from a full-carrier double-sideband modulation spectrum. We programmed our processor chip (2 × 1 mesh network) into a 2-ring SCISSOR. Each ring resonator performs a nearly ideal 1st-order all-pass filter and provides a dispersive phase response to one of the sidebands. After detection, the two phase-modified sidebands convert to two RF interference tributaries and yield a RF filter shape determined by their phase relation at each frequency component. This RF filter features high reconfigurability in both filter shape and frequency enabled by the programmable couplers and phase shifters in the ring resonators. In the experiment, we successfully demonstrated RF filter shapes varying from a 55 dB extinction notch filter to a bandwidth-tunable flat-top filter, associated with a center frequency tuning range of 1.6–6 GHz for a ring resonator's free spectral range (FSR) of 14 GHz.

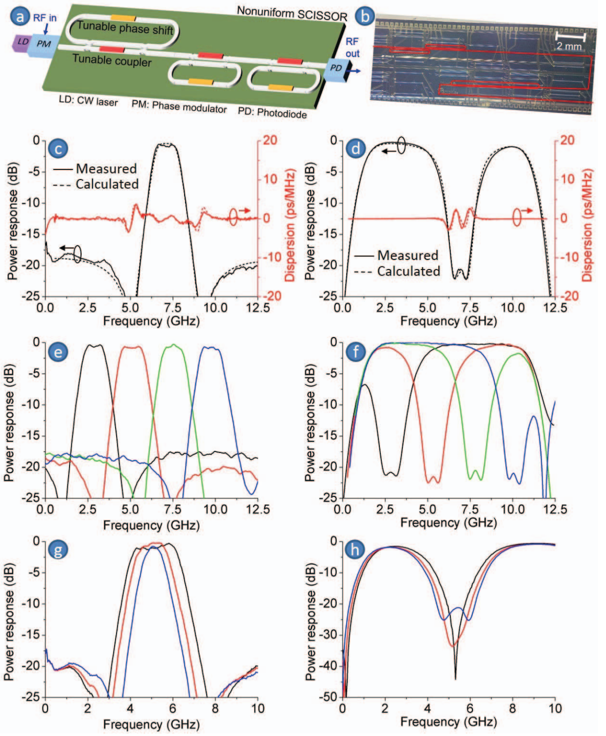

Fig. 2. (a) A schematic of an integrated microwave photonic implementation of a RF filter using a nonuniform 3-ring SCISSOR. (b) A photograph of a fabricated test chip with indications of the ring resonators. Experimental demonstrations of (c, d) the bandpass and bandstop RF filter shapes, (e, f) the tuning of filter center frequency, and (g, h) the varying of bandwidth.

While this experiment exhibits the advantage of microwave photonics in tunability, a higher degree of system integration is desirable which is critical for system stability and cost. In a more recent work [22], we reported a new implementation of such a RF filter which has potential for chip-level integration of all optical functions. The optical spectrum generation employs a serial chain of a CW laser and a phase modulator. The spectrum processing is performed by a nonuniform 3-ring SCISSOR fabricated in TriPleX^{TM} Si_3N_4 waveguide. Here, the novelty lies in that the RF filter is fully controlled by programming the couplers and phase shifters of the three ring resonators without requiring other external control mechanism, enabling full control on chip. In principle, it is possible to monolithically integrate all these optical functions including photodetectors on an InP waveguide platform, using the available building blocks [7]. Figure 2 shows the experimentally demonstrated RF filter shapes and the programmability, for which a ring resonator with a FSR of 12.5 GHz determines the RF filter between bandstop and bandpass shapes in a frequency coverage of 12.5 GHz while another two ring resonators with a FSR of 25 GHz control the filter bandwidth and center frequency as in [15].

III. OUTLOOK

Our concept of programmable processing core chip in a lattice mesh network of MZI couplers is transferrable to SOI and InP waveguide platforms that enable compact devices, particularly for large scale lattice meshes. As an advantage, InP waveguide platforms also support high-performance active functions including lasers, modulators, amplifiers and photodetectors. This facilitates monolithic integration of an entire microwave photonic system on a chip. Figure 3 shows such a chip, whose function as a microwave photonic filter has been successfully demonstrated [23]. On the other hand, however, some RF functions require long delay lines for optical processing, such as beamformers for large-scale phased array antennas and sub-GHz resolution filters. These functions impose a need for low-loss waveguide for implementing optical filters. A promising solution for this is a chip-level micro-assembly of active and passive functions. The example in Figure 3 shows such an assembly with a low-loss Si_3N_4 chip comprising a 16 × 1 beamformer circuit integrated with an InP chip providing an array of modulators [24]. In addition, this solution also allows the incorporation of compact semiconductor optical amplifiers (SOAs), which could support a significant expansion of on-chip optical signal processing capabilities; i.e. complex linear optical filters integrated with nonlinear processing functions. In two recent works [25, 26],

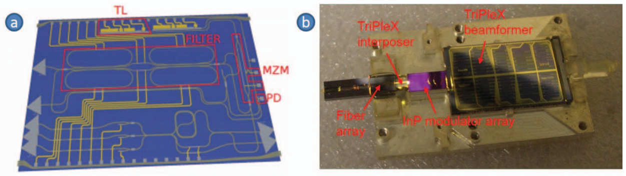

Fig. 3. (a) The layout (6×4 mm^2) of a monolithically integrated microwave photonic beat filter in InP waveguide platform (photo source [23]). (b) A chip-level micro-assembly comprising a Si_3N_4 chip of a beamform circuit and a InP chip of a modulator array (photo source [24]).

we demonstrated SOA manipulations of pulsed optical signals in optical sampling and delay discrimination which show potential for creating all-optical analog-to-digital converters.

For the PIC implementation of lattice mesh networks, the current Si_3N_4 waveguide demonstration uses resister-based heaters as thermo-optical tuning elements, which limits the minimum size of the lattice mesh geometry (Fig. 2b) and power consumption (0.25 w/π) as well as speed for programming operations. However, the recent demonstrations of tunable microrings and low-power switches in silicon [27, 28] including the advances of graphene electro-refraction modulators [29] show the potential for creating large scales of such networks with high power efficiency as well as fast tuning far beyond the kHz thermal-tuning limitation. In addition, the progress in integrated Bragg gratings [30], sub-wavelength structures [31] and plasmonics [11] open the path for THz-bandwidth signal processing devices on micrometer scales.

In addition to microwave photonic applications, recent work on integrated optical signal processors have demonstrated their applications in optical communications and quantum photonics. In [32], a PIC comprising a 2RAMZI enabled successful (de)multiplexing of 12.5 Gbaud/sub-carrier superchannels with each sub-carrier only excessing the Nyquist bandwidth by 8%. This result shows a clear advantage of PICs over free-space optics for implementing high-selectivity optical filters that enable unprecedented channel granularities (much smaller than 50 GHz) as desired in next generation elastic optical communication networks. In another recent work [33], a PIC implementation of a network of tunable couplers demonstrated a number of key processing operations for quantum computation, showing a key milestone in the study of linear universal optics. In conclusion, we anticipate a fast thriving of integrated programmable optical processors in the future across multiple areas of optics and photonics.

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