Calculating with Phase Opens up the High-Precision and High-Reconfigurability Integrated Photonic Computing

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Abstract: We propose and experimentally demonstrate a novel phase-based optical computing system integrated with photonic AD/DA converters. Further simulation shows that our system can perform 15-bit arithmetic operations when the SNR is around 34 dB.

1. Introduction

The photonic integrated circuits (PICs) promise to be an alternative to electronic processors owing to its intrinsic immunity to electromagnetic interference [1] and unprecedented operation bandwidth. The key question for constructing a competitive integrated photonic computing system is finding a natural and efficient combination between some kind of arithmetic method and some kind of controllable physical effect in photonics, just like the combination between Boolean algebra and transistors.

Almost all published photonic computing researches treat intensity as their controllable physical quantity, i.e. regard the Q in Fig. 1a as intensity, and are somewhat affected by their proven electronic counterparts. Some researches aim at replacing transistor logic gates in conventional Boolean digital system with optical ones, partially or entirely. However, optical intensity signals suffer the loss from both the material absorption and the intrinsic property of non-reciprocal Boolean operation [2], which makes optical logic gates hard to form a relatively high precision arithmetic unit. On the other hand, mainstream researches imitate the electric analog processing-in-memory (PIM) by directly mapping operands into the analog quantity of the transmissivity or transfer matrix of optical devices [3, 4]. Those optical PIM systems promise low energy consumption and ultra-short latency for the operation within the optical intensity signal. However, there are several intractable problems. Firstly, the operated analog intensity signal is susceptible to noise, which makes their calculation precision strictly limited by the relatively poor signal-to-noise ratio (SNR) and cannot currently meet the common precision requirements. Secondly, to be compatible with existing digital devices, an optical PIM operating at ultra-high frequency has to work with high-precision ADCs and DACs with a matching speed, which is highly energy-consuming. Thirdly, their speed of calibration and configuration is slow, i.e. low reconfigurability, which makes an optical PIM only able to implement relatively fixed coarse-grained operations with limited scale restricted by fixed physical structures.

The essential problem for the current integrated photonic computing is that researchers have not found a sufficiently appropriate "math partner" for the optical intensity. In this work, instead of intensity, we chose the optical phase as the physical quantity of calculation. And the residue number system (RNS), which is widely used in DSP, cryptography, and other fields [5], is chosen as our arithmetic method. With the efficient combination of the phase-based operation and RNS, we demonstrated an integrated photonic arithmetic unit with high reconfigura-

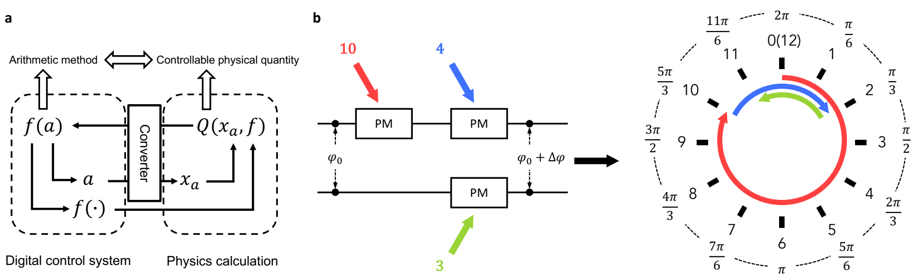

Fig. 1. a) General structure of emerging physics-accelerated computing. b) Schematic diagram of basic modular arithmetic and phase-based optical operations for the modulus of 12.

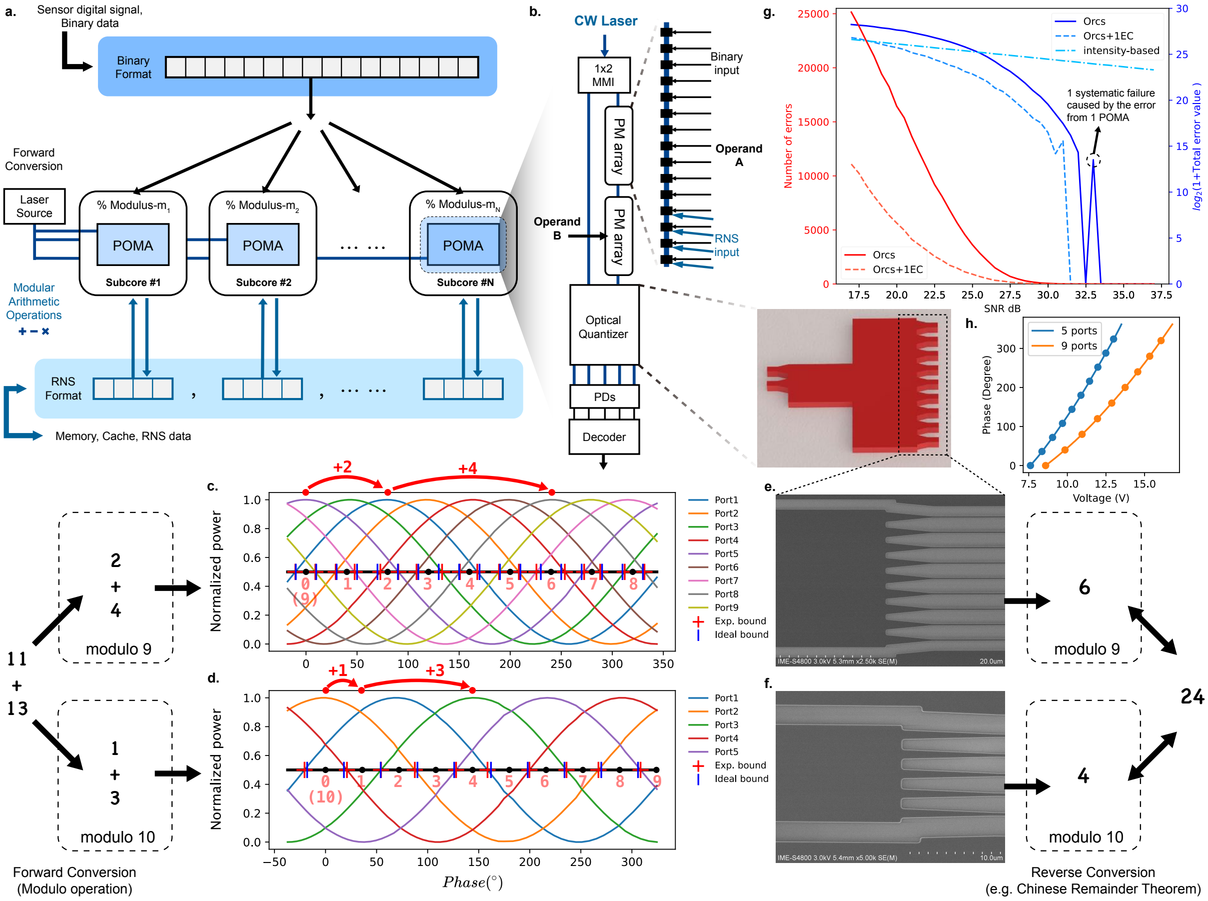

Fig. 2. a) Orcs architecture and b) POMA unit structure c,d) Experimental quantization boundaries and e,f) micrograph of optical quantizers g) Simulation results for 15-bit computing workloads.

bility and scalable-high precision. In addition, our phase-based optical computing system takes fine combination with optical ADC [6] and optical DAC, which bypass the requirement of the electric analog-digital interface.

2. Photonics-accelerated RNS computing architecture with phase-based modular arithmetic unit

RNS is a kind of unconventional number system that represents an integer number by its remainders of a set of pair-wise coprime small integers named moduli. By converting operands to RNS format with moduli set $\{m_1,\ldots,m_N\}$

$$A_{RNS} = A\%\{m_1, m_2, \ldots, m_N\} = \{A\%m_1, A\%m_2, \ldots, A\%m_N\} \tag{1}$$

, i.e. forward conversion, we break down the original calculations with high bit-width into multiple independent modular arithmetic operations with low bit-width for several kinds of basic algebraic operations. As long as within the range $M = \prod_{i=1}^{N} m_i$, the calculation results in RNS format coincide with that in conventional binary format and can be converted back (i.e. reverse conversion) . However, the relatively complex reverse conversion is always avoided by the selection of workload and the adoption of advanced residue interaction methods [5], which makes most operations implemented within RNS format and the modular arithmetic operations dominant.

Modular arithmetic is integer arithmetic in which numbers are folded by a given modulus. The periodic boundary of number representation in modular arithmetic has a natural correspondence with that of the optical phase. As shown in Fig. 1b, we mapped integers in modulo m, $\{0,\ 1,\ldots,m-1\}$, to the discrete phase difference between two adjacent waveguides, $\{0,\ 2\pi/m,\ldots,\ 2\pi-2\pi/m\}$. That mapping enables modular addition or subtraction realized by directly loading operands into the phase modulators (PMs) on the same or opposite waveguide. And to efficiently implement modular multiplication, we choose the modulus meeting the requirement of index-sum multiplication [7] that performs modular multiplication by simply a modular addition and table lookup. So far, all the basic modular operations required by RNS can be implemented via the manipulation of optical phase in that general two-waveguide structure. Fig. 2b further illustrates the concrete structure of our phase-based optical modular arithmetic unit (POMA) of a modulus, m_k. The input CW laser is split equally by a 3dB MMI. To map digital operand x into the analog quantity of phase $\Delta\varphi$ without electronic DACs, instead of a single PM, we applied a PM array that consists of cascading PMs respectively controlled by each binary digit x_i of the operand x . By designing the phase response of the i^{th} PM to the driving voltage equal to $2\pi w_i/m_k$, we map operand into :

$$\Delta\varphi = \sum_{i=0}^{L-1} x_i \Delta\varphi_i = \sum_{i=0}^{L-1} x_i w_i \frac{2\pi}{m_k} = \frac{2\pi}{m_k} \sum_{i=0}^{L-1} x_i 2^i \% m_k = \frac{2\pi}{m_k} (x\% m_k) \tag{2}$$

where $w_i = 2^i \% m_k$. When the operand is in RNS format, $x < m_k$, $\Delta\varphi = 2\pi x/m_k$, the PM array play the role of optical DAC. In addition, when the operand is in binary format, the PM array concurrently achieves the forward conversion and digital-analog conversion. All operands are modulated into optical phase in this straightforward manner, which makes POMA highly reconfigurable. Once all modulations are done, the calculation is completed and the result can be extracted by the subsequent phase-shifted optical quantizer. Our previous work [6] showed that the optical quantizer with N ports can distinguish the phase of $[0, 2\pi]$ into $2N$ quantized intervals. Then, the digital output is converted by a decoder for the following storage or computation.

As shown in Fig. 2a, the optical RNS computing system (Orcs) consists of a set of sub-cores according to the moduli set. POMAs are spread in each sub-core to parallelly perform operations. And the operating bit-width of Orcs is roughly equal to the sum of that of all sub-cores, which makes Orcs achieve high calculation precision meanwhile hold the same performance as its low-bit-width sub-cores. In addition, the Orcs possesses high scalability in precision, i.e. the improvement in precision can be simply achieved by appending more sub-cores.

3. Results

We experimentally demonstrated the basic operation of an Orcs with two moduli $\{9, 10\}$. With pre-calibrated thermal PMs (Fig. 2h), we separately loaded operands of those moduli into the discrete phase with values in the set $\{2n\pi/M | 0 \le n < M, n \in \mathbb{Z}\}$, where M = 9 or 10. As shown in Figure 2c-d, the calculation in each modulus can be regarded as the accumulation of hops over the phase set, starting from zero and finally falling into a certain phase point. To distinguish the result phase points from those phase sets, we applied optical quantizers with 9 and 5 ports. Fig. 2c-d shows the experimental quantization curves and boundaries of phase quantization interval for those optical quantizers. The phase in the cycle of 2π is approximatively evenly split into 18 and 10 sections. To fit the modulo 9, we selected every other quantization interval in the 9-port quantizer. After the calibration of the static initialized phase, the set of discrete phases were situated in the center of those chosen phase intervals, which enables us to get the unambiguous calculation results in RNS format.

We further compared Orcs with the intensity-based optical analog computing on the task of the 15-bit multiplication operation by simulation. With the moduli set of $\{7, 11, 19, 23\}$, the Orcs implemented index-sum multiplication via four POMAs that respectively deployed with $\{3, 5, 9, 11\}$ ports optical quantizers. Under different SNR conditions, independent 40000 pairs of random integer were chosen as operands. As shown in Fig. 2g, with the increase in SNR, both the frequency of error and the total error value in Orcs get a significant reduction, while the error of the intensity-based method is only slightly suppressed. Moreover, the Orcs achieve error-free 15-bit multiplication when SNR is above 33.5 dB. To improve the reliability of the Orcs, we appended redundant moduli (RRNS) to avoid small faults evolving into systematic failure. Fig. 2g shows the Orcs with one redundant POMA has the capacity to check the error from one POMA (1 EC) and further decreases the requirement of SNR.

4. Conclusion

We propose Orcs, a phase-based integrated optical computing system. By exploiting the natural similarity between optical phase and modular arithmetic, its components, POMAs, efficiently and precisely implement the operations required by RNS, while getting rid of the long-standing constraint imposed by electronic AD/DA converter by using photonic AD/DA. Under a reasonable SNR condition, the RNS-based Orcs achieves error-free high-precision calculation, which is unattainable to the current intensity-based optical computing systems.

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