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Optical computing

DOI 10.1515/nanoph-2016-0185

Optical computing has been an active topic of research for over seven decades, although solutions have been elusive. This special issue explores recent advances in all-optical information processing, including digital and analog, classical and quantum, and those based on Turing, neuromorphic, and metaphoric models of computation.

Optical computing can generally be defined as "the use of electromagnetic radiation to process information". The term "optical" is widely understood to mean "electromagnetic radiation", but the term computing is frequently assumed to lack a formal definition. In computer science, a hierarchy exists that precisely defines computational complexity, based on a combination of the amount of state and how that state is accessed. This special issue gathers papers from both perspectives, addressing issues of computation class and complexity as well as optical phenomenon from a nanophotonic viewpoint.

The quest for optical computation is arguably as old as Foucalt's knife-edge test in 1858, but the more notable activity has occurred over the past 65 years [1]. The first decades were dominated by the advent of holography in the late 1940s and lasers in the early 1960s, which combined with lens manipulations (Fourier transforms) to enable analog synthetic aperture radar (SAR) processing [1]. Room temperature liquid crystals drove research in the use of analog spatial light modulators (SLMs), which could be coupled with efficient LEDs for the first time in the 1970s [2]. That decade also brought the first exploration into optical transistors, the first foray into digital optical devices [3].

The 1980s introduced micro-electromechanical mirror (MEMS) technology and micromirrors, which provide a much more compact method for modulating arrays of light than SLMs [2]. This included new approaches for the optical transistor based on interferometers [4]. In the 1990s, vertical-cavity surface-emitting lasers (VCSELs) and the self-electrooptic effect (SEED) devices became available [5]. Research in ring resonators and more complex nonlinear optics properties became more popular in the 2000s, as did optical methods for processing network data [6]. Except for the optical transistor, much of this research focused on analog methods. The notion of optical computing in this era was limited by the assumption that device fabrication would halt at 100 nm, so nanophotonic devices might not be practical and electronic devices might have scaling limitations [7].

Although some considered the field of optical processing to have passed its peak [1], the 2010s have since seen a resurgence in activity, centering around new approaches in quantum and analog mesh and phase-based computing [8–10]. This new activity was the highlight of the OSA Optical Computing Incubator meeting in late 2015 [11] and the recent IEEE Summer Topical Meeting on Photonic Hardware Accelerators and Neuro-inspired Computing in July 2016 [12], both of which helped result in the content of this special issue.

To provide a common reference for comparison, authors were asked to address the defining properties of their type of computation, starting with the class of computation supported. These are combinatorial logic (CL), which has no state; finite state automata (FSM), which have a single state; push-down automata (PDA), which have a set of states where only the most recently-used is accessible, and the Turing machine (TM), which has a set of states that can be accessed in any order. These classes of computation also define the limit of what each can compute, e.g. a FSM cannot count because its fixed amount of state cannot be extended using positional representation to indicate arbitrary numbers. The most complex is the TM, whose capabilities define the known limits of computation.

Authors were also asked to indicate how information was represented, whether as a finite set of symbols (digitally), as analog representations of numeric values, or using analog homomorphisms (also known more recently as "metaphoric" computing). They were asked to indicate their support for reconfiguration or reprogrammability, e.g. whether this would require physical reconfiguration ("rewiring"), off-line reconfiguration, on-line reconfiguration, or true stored-program operation. Finally, they were also asked to indicate the expected use cases, i.e. the application domain of their computer.

This issue includes papers on both digital and analog data representations using both classical and quantum mechanisms. They span the variety of computational approaches, including traditional TMs, brain-inspired neuromorphic systems, and analogy-based models recently known as metaphoric computing.

Touch et al. [13] discuss classical digital optical computing and explore how information encoding encoded for long-distance transmission affects the potential for in-transit computation. They introduce the Optical Turing Machine, which requires nanophotonic implementation to integrate its computational devices composed of wave mixing, pump generation and filtering.

Krovi [14] explores the potential and limitations of optical quantum computing, including both the circuit and cluster state implementation approaches, as well as the impact of information encoding on computation. They also explore various models of quantum computation, including intermediate, adiabatic, and analog quantum computing, using the impact of the solution on computational complexity as the basis of comparison.

Davis et al. [15] discuss the role of plasmonic devices and circuits, an intermediate form between electronics and optics that integrates interesting properties of both. Plasmonics may be especially important in supporting the high bandwidths of optics with the ability to manipulate information and ease of integration of electronics.

Van der Sande et al. [16] explore the potential of neuromorphic optical computing, emulating aspects of neural networks in native optical processes. They focus on a particular variant known as the reservoir computer, which may avoid the need for explicit training by using a large system of hidden nodes with somewhat arbitrary interconnection.

De Lima et al. [17] explore the use of photonic processing as an analog computer for neuromorphic (brain-inspired) computing. They focus on the development of a processing-network node, a fundamental unit of computation in such a system and compare the properties of optical and electronic approaches to these devices.

Parihar et al. [18] explores the optical computing using coupled oscillatory dynamical systems, an example of metaphoric computing (computing by metaphor). This approach leverages the native optical processing of a set of interconnected optical devices to solve computationally hard problems. Their approach is presented in terms of insulator-to-metallic devices, but they also show how this approach can be translated to all-optical systems.

Tate and Naruse [19] explore the way in which nanostructure design can provide information security using the artifacts of fabrication. This technique can be used to store and retrieve data without the need to process data in the information domain, enabling more efficient security for optical processing.

These papers, as well as presentations and publications at other events in the past few years, indicate that the resurgence of optical computing is based on a convergence of changes: a change in the approach to computing (including quantum, dataflow, and neural architectures), a change in the algorithms of interest (focusing on communications, non-annealing relaxation, and metaphoric), and a change in the optical mechanisms being leveraged (wave mixing, entanglement and plasmonics).

Together, these changes define a new direction for the future of optical computation, one of specialization – of architectures, algorithms, and mechanisms. Some of these have been explored individually, but we are beginning to see a new “legacy free” era of investigation. This convergence, together with emerging approaches to high-density integration, is just the beginning of what we hope will be a renewed opportunity to create a collaborative community to explore the rich potential of optics to support new capabilities in computation.

Acknowledgments: This work is partly supported by National Science Foundation under Contract (1344221). Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the NSF. We also thank David Rosenbluth for his assistance in developing this issue.

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