Computer Arithmetic for Optical Computing

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The interest in parallel binary and non-binary computer arithmetic in digital computing was initiated with the pioneering works of Avizienis.[1] The parallel nature of such modified binary systems prompted researchers to adopt the modified signed-digit (MSD) algorithm for optical computing.[2] Around the same time, non-binary systems such as multiple valued logic (MVL) (Ref. 3) also achieved prominence both in optics and digital computing. Since then a large number of papers have been published in optical computer arithmetic. This special section is an attempt to capture current research in computer arithmetic for optical computing. The five major areas that are presented in this section are MSD-based algorithm and systems, optimization of MVL, novel architectures for binary optical computing, high accuracy analog optical system implementations, and system studies for fault-tolerance and accuracy. Some of the papers may have overlap of two or more areas with one primary focus; they are pointed out in the following discussion.

The largest cluster of papers appears in the area of signed-digit arithmetic and its implementation. A number of different techniques for addition, multiplication and division are proposed by several authors. The number systems addressed include redundant binary, MSD binary, negabinary, MSD trinary, recoded trinary and MSD quaternary. In terms of number of steps, addition/subtraction in single, dual and triple step has been proposed. While the MSD number system leads to higher information density, if the number of steps is reduced, the truth tables may become humongous, which may impose challenging requirements on the actual implementation. Techniques for reducing the cost of such implementations have been addressed by some authors. Proposed implementations include space-variant logic array, correlator (composite and pseudo-inverse filter) and non-holographic content addressable memory (CAM) using electron-trapping material. Several authors have proposed novel algorithms and their possible optical implementations while others have suggested implementations and/or optimization on known algorithms.

The first paper in the area of signed-digit arithmetic by Li et al. presents negabinary arithmetic operations for addition, subtraction and multiplication and implements them using electron trapping material. A carry free addition technique in signed-digit negabinary (SDN) is presented with a conversion technique from SDN to normal negabinary. Zhang and Karim propose modified two-step, one-step, canonical and three-input algorithms for addition of redundant binary numbers and provide architecture and encoding for corresponding optical space-variant implementation. Cherri demonstrates single step trinary and quaternary signed-digit circuits. In general, the reduction in step increases the complexity of the truth table. However, Cherri overcomes the problem by smart digit grouping to reduce the number of rules and an intelligent pixel encoding to implement the system within a certain space-bandwidth product. Huang, Itoh and Yatagai propose a new technique for high-speed 2-D data array addition and multiplication based on binary MSD addition and digit-decomposition-plane representation. Huang, Itoh and Yatagai generate all the partial products in parallel and propose to add them using an MSD adder tree. It is interesting to note that they perform multiplication operation using five elementary operations such as bitwise product, duplication, shifting, masking and magnification. In the next paper, Alam introduces trinary division technique based on recoded trinary addition and multiplication. The proposed implementation uses a pseudo-inverse filter correlator. The last two papers in this group by Ahmed, Awwal and Power and by Zhang and Karim propose novel implementations of trinary and binary MSD algorithm. Ahmed, Awwal and Power implement an MSD trinary adder using composite phase-only-filter correlator architecture. In this framework, the truth table rules are encoded as a composite filter. They develop a specific encoding of the inputs which allows the composite filter to produce outputs detectable with a simple threshold formulation. Zhang and Karim implement their MSD circuit using binary encoding of MSD numbers and three-step addition technique. Their implementation uses spatial encoding of the inputs and a programmable decoder mask at the output plane.

The next paper deals with optimization of logic functions. Optimization is necessary for efficient implementations of computing devices. Awwal and Iftekharuddin demonstrate a *K*-map[4] type of technique for minimizing MVL logic functions. They also show how the minimized functions can easily be implemented optically. Two other papers, in the previous section, by Cherri and by Huang, Itoh and Yatagai demonstrate optimization of MVL logic as well. Their technique involves an interesting variation in reduction methodology wherein minimization is achieved by decomposing the function into multiple subgroups that can be combined to generate various output functions. Such minimization based on subgroup sharing is equivalent to truth table partitioning that is usually prevalent in ROM based circuit optimization.[4]

The area of optical computer architecture is always fascinating, as it offers us many possible means for realistic system implementations. McAulay proposes a novel architecture for binary logic computation based on the guided wave approach to perform computations. McAulay systematically builds up his case for an arithmetic adder circuit from the ground up by constructing basic logic primitives using directional couplers and synchronized laser sources. The paper compares two proposed binary adder implementations: one with digital and mixed analog elements, and the other with strict digital binary logic elements. McAulay puts forth convincing evidence for utilizing the delicate phase component of fiber-guided optical signal to attain digital accuracy.

Recent interests in optical computer arithmetic include studies of soft computing as opposed to strict binary-based computation. It is anticipated that strengths of analog optics may be harnessed more efficiently by using something in between strict binary and pure analog. MVL, fuzzy logic and interval arithmetic are all good candidates for soft computing. The next group of three papers falls in this category. The first paper in this group by Jiang and Li discusses fuzzy systems, the second by Sasaki, Tanida and Ichioka demonstrates how to use analog optics to get digital accuracy, and the third by Caulfield shows how to achieve quick yet moderately accurate solutions for limited accuracy optical arithmetic components. Jiang and Li derive analytical results for digitized fuzzy logic operations such as union, intersection and complement in terms of sum of product operation which is implementable using non-holographic CAM. They discuss how to parallelize a fuzzy function using binary encoded parallel optical techniques. They benchmark their fuzzy algorithm against known parallel digital techniques. It is interesting to note that their results are also applicable to the digital domain. Sasaki, Tanida and Ichioka demonstrate high accuracy computation for calculating fixed-point affine transform employing interval arithmetic. Their work is perhaps motivated by the possibility of utilizing fast feedback using analog optics, and self-correction and convergence offered by the fixed point theorem. They offer both theoretical insight and practical demonstrations using an optoelectronic self-correcting loop with TV-detector systems. Caulfield uses chaos and stochastic resonance to achieve limited accuracy results. While Sasaki, Tanida and Ichioka opt for an optical high accuracy system with feedback, Caulfield uses optics to obtain reliable initial solutions and then suggests using digital electronics to obtain higher accuracy results.

Improving fault-tolerance and system studies is the last category. Yellampalle and Wagner discuss redundant interconnects for fault tolerant digital optical computing and presents an error analysis for the same. They show an optical architecture for a quadded system using holographic interconnects. Their architecture uses redundant optical logic schemes to offer small error probabilities and low system error rates. Iftekharuddin, Awwal and Chowdhury present engineering analysis of issues for practical implementation of MVL circuits using optical logic gates. This paper attempts to address thresholding problems with implementing optical systems using MVL in terms of signal-to-noise ratio.

In the future, as the field matures, we hope to see more work in the areas of systems studies, which will address the optical computing system implementation issues. In order for people to rely on such systems for serious computation works, fault tolerance needs to be investigated more thoroughly. Some of the interesting ideas presented in this issue may lead the researchers to new directions in this exciting field. We would like to thank all the contributors for contributing to this special section, the reviewers for timely review of the papers selected here, and the *Optical Engineering* staff for their support and cooperation.

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