Optical Computing Systems

Sobha Gottipati
Prathima Rao
Anjali Panicker
Introduction

- "Optical Computing" means the use of light as a primary means for carrying out numerical calculations, reasoning, artificial intelligence, etc.

- The field of optical computing is quite broad. Optical computing provides the first in-depth review of the possibilities and limitations of optical data processing.
Introduction

- The partial listing of those points that make optical computing appealing are:
  - Direct Image Processing
  - Massive parallelism and connectivity
  - Speed
  - Immunity to electromagnetic interference (EMI)
  - Size and cost
History & Trends

- The “ancient” history of optical computing is linked to that of radar systems. Optical computing system received a great push from the invention of laser in 1960.

- There are three distinct trends in optical computing:
  - Special purpose analog optical systems
  - General purpose Digital optical computers
  - Hybrid Optical/Electronic systems
Optical Information Processing

Articles:

1. “Optical Information Processing”
   Allan Gillespie

2. “Materials for Optical Computing”
   B.S. Wherrett
Optical Information Processing

- Prospects for the use of optics in information processing, stem from the non-interacting nature of photons which results in high potential time / space bandwidth.
- It is a rapidly expanding subfield and the concepts are essential to understanding optical computing and real-time optical image processing.
- This article introduces some basic concepts of optical processing from the viewpoint of Fourier optics using
  - spatial filtering
  - holography as examples
Spatial Filtering

Fig.1: faithful image of a portion of 625-line TV image.
Fig.2: image of (fig.1) after filtering to block raster.
Spatial Filtering

- Spatial Filtering is a process by which we can alter properties of an optical image by selectively removing certain spatial frequencies that make up an object.
- See figure.

Uses:

- To filter video data received from satellite and space probes.
- Removal of raster from a television picture or scanned image.
Holography

- It is a photographic method of recording information about an object which enables us to construct the object in three dimensions.

- Holography relies on the encoding of the object formation in a set of complex interference fringes formed by the interaction of a plane coherent reference wave with the wavelets diffusely scattered by the object.
Hologram

- The microscopic interference fringes recorded on a high resolution photographic plate after development and processing become ‘hologram’.

Applications:
- To study small deformations of objects.
- To replace conventional optical elements such as lenses and beam splitters.
- For data/information storage.
- Use of photo refractive materials in analog computing, object recognition and correlation to name a few.
Conclusion

- Spatial filtering, holography and other concepts in Fourier optics have become increasingly important in photonics, since they lay a foundation for the understanding of more modern topics such as optical computing, optical neural networks, phase-conjugate optics and image processing using refractive materials.
Materials for optical computing

- In 1960s the first schemes for all-optical digital computers were proposed.
- In 1990s emphasis has shifted to optical interconnection of arrays of semiconductor smart pixels.
- This article presents reasons for such shift and also proposes natural materials such as bacteriorhodopsin as possible material for optical computing.
Materials for optical computing

- All optical processing:
  - Optically based processors employed nonlinear optical resources either of liquid crystal spatial light modulators (SLMs) or nonlinear interference filters (NLIFs).

- Electroabsorption devices:
  - Bridge between all-optical demonstrators and optically interconnected smart pixels.

- Optically interconnected smart pixels:
  - Chip to chip interconnection is optical; logic and local on-chip interconnection is electrical. They have several advantages like faster data acquisition, low power consumption over all-electronics systems.
Optical Based Parallel Processor Architecture
Materials for optical computing

- In the context of digital computing, bacteriorhodopsin, present in halobacteria halobium provides a memory of lifetime about 10s, that can be written to and read from short pulses.

- The message to be given is that there may well be clues from the biological world about materials and mechanisms that have application to optical computing and that may operate with the required combination of properties.
Despite the shift to an evolutionary approach to the increased use of optics within computing there are many more material challenges to be met.

It is most unlikely that all optical digital computers will be built without a major breakthrough in nonlinear optics.
DIGITAL OPTICAL COMPUTING

- “Digital Optical Computing” by Suzanne Wakelin and Andrew C Walker
- “Visual Area Coding Technique for Parallel Digital Optical Computing” by Jun Tanida and Yoshiki Ichioka
Digital Optical computing

- Optical Techniques can provide a number of ways of extending the information processing capability of electronics.

- Large quantities of data can be generated from different resources and powerful computer is required to process them.

- Just electronics are not enough for this and therefore OPTICS can provide some solutions.
Digital Optical computing

- There are a number of advantages in using optical means of transferring data instead of electrical connections.
  - The information can be coded in parallel fashion.
  - No EMI.

- The optical processors have to be compatible with existing electronic systems. Free space digital optics is one direction that provides some valuable solution. Digital Optical computer requires the use of nonlinear optics.
Optical Switches- SEED

- In electronics, the transistors act as logic gates that carry out the processing operations.

- The analogous component in optical processing is a switch.

- A switch that is sensitive to input light and gives optical output is the **Self Electro-optic Effect Devices (SEEDs).**
Optical Switches- SEED

- SEEDs rely on changes in the optical transmission of a semiconductor induced by an applied electric field.

- SEEDs are made by placing a multiple quantum well (MQW) structure between p and n doped layers. This creates an electrical diode which is reverse biased by applying a voltage across p and n regions.
Optical Switches- SEED

- The schematic diagram of a SEED in a resistor biased circuit.

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Light in
resistor

n  l  p

Light out
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Symmetric SEEDs

- SEEDs can be configured in pairs so that a beam of light switching one device can cause a complementary switch in the transmission of the other.

- Hence, a small change in the intensity of one beam can cause a large change in intensity of the other. This kind of configuration is known as Symmetric SEEDs.

- Symmetric SEEDs can be created by electrically connecting two SEEDs in series.
Symmetric SEEDs

- This combination acts like an electronic flip-flop and permits logic operations NAND and NOR to be carried out on pairs of optical input signals.

- With symmetric SEEDs, the higher the input optical power, the faster the switching speed.
Symmetric SEED CLIP

- **Cellular Logic Image Processor (CLIP)** is implemented using the Symmetric SEEDs.

- CLIP computer architecture is designed to permit parallel information processing, in which logic operations are performed on each element of the array simultaneously.

- One such system is shown:
Symmetric SEED CLIP
Symmetric SEED CLIP

- This system has 2 arrays of symmetric SEEDs optically connected in a loop.
- A spatial light modulator (SLM) was used to write the input image onto the first device array. The image is read out optically and imaged in parallel.
- The output of this device array then passes through a computer designed hologram that splits each beam into two and sends this information to the corresponding nearest neighbor on the 2nd SEED array.
- The output from the 2nd device is then looped round as a new input to the first array, using bulk optics, while further images can be input simultaneously using the SLM.
Symmetric SEED CLIP

- **Uses:**
  - Two input NAND or NOR logic operations can be performed at each device array.

- **Practical Uses:**
  - Systems of this kind allows one to implement simple image processing tasks such as target-tracking, maze-solving and noise removal.

- **Future:**
  - More complex devices incorporating more electronic logic will be operated as the device technology develops.
OPALS and VACT

- OPALS is an Opt-Electronic Hybrid Computing System that has a potential capability of optical information processing based on digital computing Scheme.

- Here an implementation of digitized- analog optical computing named Visual Area Coding Technique (VACT) is considered as an example of visible information processing.
Concept of VACT:

- It is based on:
  - Coded Pattern Processing: It is a class of optical computing technique where information is converted into spatial coded pattern and optical processing is applied to process information in parallel.
  - Digital Halftoning: It is a technique to display gray level images with binary intensity. e.g. Black and white.
In VACT we merge the 2 techniques.

**TECHNIQUE:**

- Information with discrete states (e.g. Gray level of the image) is the objects. This information is converted into visual area codes, using digital halftoning.

- Once the visual area codes are obtained, various processing can be executed with simple operations such as signal-level inversion, spatial inversion, discrete correlation etc.
VACT

Fig. 1 Conceptual diagram of VACT
Application of VACT:
- Morphological image processing

Conclusion:
- VACT is still in the experimental stage. But it is very promising since visibility is one of the most attractive features of optical processing.
Hybrid Optical/Electronic Systems

- Articles:
  
  "Performance evaluation of optoelectronic processing systems based on device area resources", Jun Tanida.

  "Optoelectronics-VLSI system integration Technological challenges", Marc P Y Desmulliez.
Introduction

- The author does a simple evaluation of optoelectronic processing systems in terms of
  - Available chip area.
  - Processing capability of the electronic circuits.

- A parallel processing system composed of multiple processing elements with an interconnection network over the processing elements is investigated.
Target optoelectronic processing system

Shaded part indicates optical subsystem and non-shaded part is the electronic subsystem.
Two types of system packaging methods evaluated in terms of size and functionality of each processing element are:

→ In-plane packaging.

→ Stacked packaging.
Evaluation by chip area

- The dominant factors limiting processing element density on the substrate are all related to optical signal transmission. Of these, the author finds optical system diffraction to be the most restrictive limitation.

- The pixel size ranges from several tens of micrometers to several hundreds of micrometers due to the size of photo detectors.

- This value is relatively larger than the diffraction limited value. As a result the only effective way of increasing the number is to enlarge the chip size.
Evaluation of processing capability with equivalent chip area

Assumptions -

- The data to be processed is distributed over the processing elements and the processing elements communicate with each other during processing.
- Data processing and data communication cannot be executed concurrently.
- In-plane packaging system is examined to equate the chip area between the two systems.
Evaluation of processing capability with equivalent chip area

- For the optoelectronic system, a task $W$ is divided in the ratio of $(1-A): A$ for the subsystems.

- For the pure electronic system the entire task is achieved by the electronic circuitry.

- Author evaluates the performance of the two systems and finds that the task ratio $A$ (ratio of optical data communication) impacts the performance of the electronic circuits in an optoelectronic system.
Evaluation of processing capability with equivalent chip area

- Except in two distinct cases, the optoelectronic system was found to have a performance capability inferior to that of the pure electronic system.

- When the task ratio $A$ is close to zero where optical communication is used in a limited place like a system with a small number of optical links.

- When $A \approx 1$ where optical processing dominates most parts of the task as in optical signal router and optical exchange systems.
Conclusion

- The evaluation on the size of each processing element strengthens the case for space-effective design.

- The comparison of processing performance of the electronic circuits between the optoelectronic system and the pure electronic systems emphasizes the importance of selecting applications suitable for optoelectronic implementation.
Logic complexity and design issue

- Optoelectronics-VLSI technology is inherently a multidisciplinary field.
- The diversity of backgrounds can be an obstacle in the design process.
- The available optical power at the photo detectors determines the minimum processing time available, that is the maximum pixel operating frequency.
- The optimum performance of hybrid processing elements depends on a narrow set of parameters that is independent of the architecture and technologies used.
Logic complexity and design issue

- This set of parameters dictate that the optimum system performance occurs when the optical data-rate per data channel matches the electronic processing rate.

- The smart-pixel array would not make use of the optical bandwidth offered by optics if it has a low number of optical channels, unless multiplexors and demultiplexors are used.
System Integration Issue

- The optoelectronic components have quite different optical and electronic qualities.

- The tradeoffs in characteristics such as chip drive power, inter chip connectivity density and fan out capability will dictate the choice of the device used.

- For example, VCSEL (Vertical cavity surface emitting lasers) have excellent fan out capability and moderate inter chip connectivity density but poor chip drive power.
Assembly and Testing Issues

- The high-aggregate bandwidth is useful only if the data to be processed can be fed into the system and be output on a timescale comparable with the processing time.

- For optical input/output data beams, the problem lies in the concentration of 100 to 1000 optically parallel, equally spaced channels within a chip-compatible area.

- This requires precise assembly and opto-mechanical control of the beams in the case of free space optics.
Assembly and Testing Issues

- Electrical input/output data stream frame rate limitations requires on-chip memory registers to handle the situation.

- Such a situation is also likely to occur for the testing of such systems since the present electronic testing equipments are unlikely to cope with the tremendous aggregate bandwidth generated by such systems.
Conclusion

- While optoelectronic devices have become reliable and show performance factors compatible with electronic processing, more work needs to be carried out on the integration aspects of this technology at the device, interfacing, system assembly and testing levels.