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Optical Architecture for Modern Computing Systems

1. Introduction

Modern computing systems face many challenges such as increasing data volume, energy consumption, heat generation and latency. Conventional computing hardware based on electronic transistors and von Neumann architecture cannot satisfy the growing demand for high-performance computing due to the limitations of Moore's law and Dennard's scaling rules. Therefore, alternative approaches and architectures are needed to overcome these challenges and enable new applications of artificial intelligence (AI) and machine vision.

One promising solution is optical computing, which uses light instead of electricity to perform computation. Optical computing offers a lot of advantages over electronic computing, such as:

- Higher speed: Light can process information instantaneously with negligible delay.

- Lower energy: Light can transmit information with minimal loss and heat dissipation.

- High parallelism: Light can carry multiple bits of information simultaneously using multiplexing schemes such as wavelength division multiplexing (WDM) and mode division multiplexing (MDM).

- High bandwidth: Light can access a wide range of frequencies from infrared to ultraviolet, providing a large capacity for data transmission.

Optical computing can be classified into two categories: digital optical computing and analogue optical computing. Digital optical computing mimics the logic operations of electronic transistors using optical components such as switches, gates and memories. Analogue optical computing exploits the physical properties of light such as interference, diffraction and nonlinear effects to perform complex mathematical operations such as vector/matrix manipulation, reservoir computing and Ising machine.

In this report, we will focus on analogue optical computing as a potential architecture for modern computing systems. We will outline the performance advantages and limitations of analogue optical computing and describe the main components that it is made up of.

2. Analogue Optical Computing

Analogue optical computing is a form of computation that uses continuous values of light intensity or phase to represent data. Analogue optical computing can perform various tasks that are difficult or inefficient for electronic computers, such as:

- Vector/matrix manipulation: Analogue optical devices can implement linear algebra operations such as matrix multiplication, inversion, eigenvalue decomposition and singular value decomposition by using spatial light modulators (SLMs), lenses, holograms or interferometers. These operations are essential for many AI applications such as image processing, computer vision and machine learning.

- Reservoir computing: Analogue optical devices can implement a type of recurrent neural network (RNN) called reservoir computing by using nonlinear media such as photorefractive crystals or fibre loops. Reservoir computing can perform temporal processing tasks such as time series prediction, speech recognition and natural language processing by exploiting the dynamical behaviour and memory capacity of the nonlinear media.

- Ising machine: Analogue optical devices can implement a type of optimization algorithm called Ising machine by using coupled lasers or degenerate optical parametric oscillators (DOPOs). Ising machine can solve combinatorial optimization problems such as traveling salesperson problem, graph colouring and spin glass model by mapping them onto an Ising model and finding its ground state using feedback mechanisms.

3. Performance Advantages

Analogue optical computing has several performance advantages over electronic computing in terms of speed, energy efficiency, scalability, and flexibility.

- Speed: Analogue optical devices can operate at ultrafast speeds ranging from picoseconds to nanoseconds due to the short response time of light-matter interactions. For example, an analogue optical matrix multiplier based on SLMs (SLMs refers to Spatial Light Modulators which are devices used to modulate the intensity of light in two dimension) lenses can achieve a speed of 10 teraflops per second, while an analogue optical reservoir computer based on photorefractive crystal can achieve a speed of 1 gigaflop per second.

- Energy efficiency: Analogue optical devices can consume much less energy than electronic devices due to the low power requirement of light sources and detectors. For example, an analogue optical matrix multiplier based on SLMs and lenses can consume only 0.5 picojoules per operation, while an analogue optical reservoir computer based on photorefractive crystal can consume only 10 nanojoules per operation.

- Scalability: Analogue optical devices can scale up easily by increasing the number or size of light beams or modes without affecting their performance significantly. For example, an analogue optical matrix multiplier based on SLMs and lenses can scale up to thousands or millions of dimensions by using WDM or MDM schemes, while an analogue optical reservoir computer based on photorefractive crystal can scale up to hundreds of nodes by using MDM schemes. Ising machine based on coupled lasers or DOPOs can scale up to thousands of spins by using WDM schemes.

- Flexibility: Analogue optical devices can adapt to different tasks and scenarios by changing the parameters or configurations of light sources, detectors, modulators, or feedback mechanisms. For example, an Analogue optical matrix multiplier based on SLMs and lenses can change the input and output matrices by updating the SLM patterns, while an Analogue optical reservoir computer based on photorefractive crystal can change the input and output weights by adjusting the feedback gains.

4. Performance Limitations

Analogue optical computing also has some performance limitations that need to be addressed or mitigated, such as:

- Accuracy: Analogue optical devices may suffer from noise, distortion, crosstalk, or nonlinearities that affect the quality and precision of computation. For example, an analogue optical matrix multiplier based on SLMs and lenses may introduce phase errors due to imperfect alignment or aberrations, while an Analogue optical reservoir computer based on photorefractive crystal may show saturation effects due to high input power.

- Stability: Analogue optical devices may be sensitive to environmental factors such as temperature, humidity, vibration, or dust that affect their operation and reliability. For example,

an analogue optical matrix multiplier based on SLMs and lenses may require active cooling or stabilization systems to maintain optimal performance, while an analogue optical Ising machine based on coupled lasers may require careful tuning or injection locking to achieve synchronization.

- Programmability: Analogue optical devices may have limited flexibility or scalability in terms of changing their functionality or architecture according to different tasks or problems. For example, an Analogue optical matrix multiplier based on SLMs and lenses may have a fixed size and shape that limit its applicability for different dimensions or types of matrices, while an Analogue optical Ising machine based on coupled lasers may have a fixed topology that limit its mapping capability for different optimization problems.

5. Components

Analogue optical computing systems are composed of several components that perform distinct functions such as:

- Light processors: These are devices that perform computation with light beams using physical principles such as interference diffraction or nonlinear effects. Examples of light processors include lenses holograms or nonlinear media.

- Light sources: These are devices that generate light beams with desired properties such as wavelength, power, polarization, coherence, or modulation. Examples of light sources include lasers, LEDs, or supercontinuum sources.

- Light detectors: These are devices that measure light beams with desired properties such as intensity, phase or spectrum. Examples of light detectors include photodiodes photomultipliers or spectrometers.

- Light modulators: These are devices that manipulate light beams with desired properties such as amplitude phase or polarization. Examples of light modulators include SLMs liquid crystal modulators or electro-optic modulators.

- Feedback mechanisms: These are devices that provide feedback signals to control or optimize the operation of light sources, detectors, modulators, or processors. Examples of feedback mechanisms include electronic circuits, optical switches, or neural networks.

6. Optical Architecture Instruction, Data Execution and Storage

The system will consist of four main components: an optical processor, an optical memory controller, an optical interconnect network, and an optical main memory. The optical processor performs computation with light beams using photonic crystal devices such as waveguides, splitters, couplers, modulators, switches, filters, resonators etc. The optical memory controller manages the access to the optical main memory and optical cache levels (PhC SRAM cache which stands for photonic crystal static random-access memory a type of volatile memory that uses light to store and retrieve data) The optical interconnect network connects the optical processor with the optical memory controller using waveguides or fibre-optic cables. The optical main memory stores data on O-PCM disks which stands for optical phase-change memory, which is a type of non-volatile memory that uses light to store and retrieve data.

The instruction, data execution and storage process can be described as follows:

- The processor fetches instructions from the PhC SRAM cache level using light beams modulated by SLMs.

- If there is a cache miss at the PhC SRAM level, the processor requests instructions from the O-PCM cache level using light beams modulated by SLMs.

- If there is a cache miss at the O-PCM level, the processor requests instructions from the main memory using light beams modulated by SLMs.

- The memory controller receives the instruction requests from the processor and sends them to the appropriate memory devices using light beams modulated by SLMs.

- The memory devices read or write instructions on their media using laser beams focused by lenses or holograms.

- The memory devices send back instructions to the memory controller using light beams modulated by SLMs.

- The memory controller sends back instructions to the processor using light beams modulated by SLMs.

- The processor executes instructions on its photonic crystal devices using light beams manipulated by various physical principles such as interference, diffraction, or nonlinear effects.

- The processor accesses data from the PhC SRAM cache level using light beams modulated by SLMs in an equivalent way as it accesses instructions.

- If there is a cache miss at the PhC SRAM level, the processor requests data from the O-PCM cache level using light beams modulated by SLMs.

- If there is a cache miss at the O-PCM level, the processor requests data from the main memory using light beams modulated by SLMs.

- The memory controller receives the data requests from the processor and sends them to the appropriate memory devices using light beams modulated by SLMs.

- The memory devices read or write data on their media using laser beams focused by lenses or holograms.

- The memory devices send back data to the memory controller using light beams modulated by SLMs.

- The memory controller sends back data to the processor using light beams modulated by SLMs.

To handle cache misses efficiently, optical computing systems use various techniques such as prefetching, pipelining, parallelism, and coherence protocols. [1] Prefetching is a technique that anticipates future data requests and fetches them in advance from lower levels of memory. Pipelining is a technique that divides a cache miss operation into multiple stages and overlaps them with other operations. Parallelism is a technique that exploits multiple light beams or modes to access various parts of memory simultaneously. Coherence protocols are techniques that ensure consistency among different copies of data stored in distinct levels of memory.

Optical Cache Level	Optical Cache Size	Average Time Access	Average Miss Rate
O-PCM	32 MB	10ns	5%
PhC SRAM	256 KB	1ns	0.5%

The table shows that higher optical cache levels have smaller optical cache sizes but also shorter access times and lower miss rates. O-PCM stands for Optical Phase Change Memory and PhC SRAM stands for Photonic Crystal Static Random Access Memory. These are two types of optical memory devices that can be used for optical caching. O-PCM has a larger capacity but a longer latency than PhC SRAM.

7. CONCLUSION

In this report, we have learned how optical computing works and what are its advantages and limitations. We have seen how light beams can be used to perform computation and store data using optical devices such as lasers, lenses, modulators, and nonlinear media. We have also seen how an optical computing system can have an all-optical cache hierarchy using O-PCM and PhC SRAM to speed up memory access. We have also discussed some examples of applications that can benefit from optical computing such as vector/matrix manipulation, reservoir computing and Ising machine.

Analogue optical computing is a fascinating technology that has the potential to revolutionize the field of computing by offering faster, more efficient, and more scalable solutions than electronic computing. However, optical computing also faces some challenges such as accuracy, stability and programmability that need to be overcome or mitigated. Optical computing is still in its infancy and requires more research and development to become a viable alternative or complement to electronic computing.

We hope you enjoyed reading this report and learned something new about optical computing. We hope you also appreciate the beauty and complexity of light and how it can be used for amazing things. Remember that light is not only something that we see with our eyes, but also something that we can use with our brains.