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Optical computing: an overview

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ABSTRACT

Moore's Law has been greatly depended upon for the development of Electronic computers as they have also been regarded as traditional computers which cannot meet the high speed and bandwidth demands of the future. This led to the emergence of researchers in the field of computer engineering that began to work towards optical computing systems. Therefore, this paper seeks to examine optical computing as one of the major trends in Information Technology (IT) industry in the perspectives of its pros and cons towards recommendations that will further improve IT industry.

Introduction

The optical computing systems are computers that employ photons to process information rather than electrons through the development of optical transistor. In a nut shell, an optical computer (also called a photonic computer) is a device that uses the photons in visible light or infrared (IR) beams, rather than electric current, to perform digital computations. This development is one of the recent technologies that are on the verge of bracing the trail in computer engineering (Rui Natário 2011)

Knight (2012) posits that 'optical processing has developed alongside electronic processing. Optical processing, however, has long been tied to analog processing because the digital processing was not attainable. It is for that reason that digital computers are purely electric, while high bandwidth transmission is optic.' In essence, the development of optical processor dates back to over 60 years in order to meet demands that electronic computers could not meet.

Initially, Optical computer architecture comprises an input plane, a processing plane, and an output plane. By this, a spatial light modulator (SLM) changes an electrical signal into an optical signal. The signal is then transferred through a lens that would output the Fourier transform of the original signal.

With the development of laser, much interest was generated in the field of optical computing. Though, it is important to mention that getting or producing dependable SLMs posed a great challenge. Therefore, there was enormous expansion in the field of electronic computers. Yet this, researches in1990's brought positive development to optical computing as optical processing units began to be integrated into traditional computers, hence, a prototype of an optical correlation that would fit into a PCI slot and be capable of processing 65MB/s of video was developed, but was not commercialized.

The initial optical processors were analog and there came an increasing need to develop digital optical processors so that for the purpose of commercialization. Already, the advancement of optical interconnects allowed for the use of fiber optic cable as a means of transmitting data. Wavelength division multiplexing, optical amplifiers and switches have pushed optical transmission into the mainstream for high bandwidth demands. The same bandwidth and speed is desired for inside the computer, not just between. Hence, Intel came up with a research in 2009, on optical interconnects between chips, which allow for 1 THz bandwidth. Today, as rightly noted by Knight (2012), a large amount of research is being done in the area of optical transistors.

Many methodologies have been proposed and tested (Alven 2008). Once an optical transistor is developed that successfully competes with an electrical transistor, digital optical processors will begin to replace their electrical brothers as the main paradigm for digital information processing. In the same vein, others are being worked on.

Objectives

The paper is meant to achieve the following objectives in respect of optical computing:

i) Appraisal of the development of optical computing;

ii) Emphasy on methodologies of optical transistor; and

iii) Discussion of advantages and disadvantages of optical computing.

Optical Transistor Methodologies

It is expected that the new system of digital processing may also open the doors to other types of processing which are not possible with traditional computers. The key to modern optical processing is the optical transistor. Transistors are the basis of digital logic, acting as switches that control voltage levels in electronics. According to ITU-T Technology Watch Report (2011) Optical transistors are expected to act the same way, controlling light levels within a fiber optic network. The other condition for digital light processing is the small scale of integrated circuits. Optical pathways must be created on a very small scale to be competitive with electronic circuits. Several companies and educational institutions have been in a mad rush to discover the almost mystical optical transistor. Different materials and strategies for controlling the flow of light have been devised, with the hopes of commercializing the technology and increasing the ability of modern computers to handle the ever increasing needs of society. This could be through different methods as identified by Knight (2012) thus:

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On-chip Optical Interlink

Fiber optic data links are used to transfer data between servers and to other areas, but the signals still require copper cabling ins and around the server. On-chip Optical Interlinks have a small silicon laser embedded directly on the chip so that the high bandwidth optical signal can be sent directly. This greatly reduces the amount of cabling required for server processors to make the necessary connections. Silicon photo-detectors embedded on the chip provide the optical sensing needed to receive optical transmissions. It is noted that the concept of replacing traditional copper cable within computers with the optical equivalent will soon become commonplace. The transmitter is fabricated in a similar manner as the chip itself allowing for data transmission between devices of 10 GB/s, 20 times faster than USB (Halfacree 2010).With higher powered servers in mind, Hewlett-Packard has begun to use optical waveguides carved into plastic with metal reflectors to route optical data within servers, instead of using optical interconnects. These waveguides can be manufactured in the same fashion as a compact disk. IBM has begun mounting optical transmitters on chips to speed data flow between the cores of multicore processors. All of these ideas have been around for some time, but the technology to produce these chips is just now coming into play

Two Symmetric Microring Resonators

A breakthrough occurred in 2004 at the Laboratory of Physical Sciences where an all-optical NOR gate was demonstrated using symmetric GaAs-AlGaAs microring resonators, whose resonances were closely matched. Two input data streams were tuned to one resonance of the symmetric microrings to switch a probe beam tuned to another resonance by two-photon absorption. The energy needed to switch the gate is 20 pJ/pulse with a switching window of 40 ps (25 GHz)(Ibrahim et al 2004).

Potential and Ion-switched Molecular Logic Gate

This logic gate exists at a molecular level and uses the photoluminescence and absorption properties of specific compounds to control photon signals. At the time, several nanoscale optical logic gates had been demonstrated, but these examples could only exist in solution and therefore were limited in the amount of connections that could be made. The logic gate uses a nanocrystaline thin file TiO_2 substrate with a specific compound absorbed at the surface. When excited by a combination of chemical and electrical signals, the compound would exhibit a strong metal-to-ligand charge transfer which results in strong luminescence (Levy 2011).

Silicon Based Photodiode and Waveguide

At MIT, silicon based photo-diodes, which limit optical transmission to a single direction, have been developed. The technology replaces previous devices which were large and made of exotic materials. The photo-diode is capable of isolation up to 19dB at 1550nm. The device is 290μm in length. The importance of this development is that it opens the door for designing integrated optical circuits. "The design of the circuit can be produced "just like an integrated-circuit person can design a whole microprocessor. Now, you can do an integrated optical circuit," said Caroline Ross, the Toyota Professor of Materials Science and Engineering at MIT (Brown 2011).

Passive Optical Diode

Researchers at Purdue University have also developed a photo-diode out of silicon. This device uses photon interactions with two silicon rings measuring 10μm in diameter to control the flow. Whenever light enters from one ring, it passes through the system, while light entering from the other ring is blocked and dissipated backwards. The forward-backward transmission ratio is up to28dB.

Benefits and Drawbacks of Optical Computing.

Benefits.

Optical computers will only be produced if they are cheaper or more powerful than conventional ones (or best: both of it at the same time). Besides hybrid solutions there will be a competition between the two different kinds of computing. To be able to measure optical computers and their future possibilities, conventional computers and their actual stage of development concerning each advantage and disadvantage are depicted. Advantages of optical computers compared to conventional computers are:

Higher Performance

The most significant advantage of optical computers is the potential of higher performance. A concrete benchmark test between optical and conventional computers is not possible yet. But the performance of an optical computer in an advanced stage should be several orders of magnitude higher. A computer based completely on optical components is the optimum concerning speed: Full optical RAM saving photons directly if possible or otherwise indirectly, bus systems using concentrated light beams (lasers) to communicate, optical processors and holographic drives. All those components have the capability to be much faster than the existing electric ones. For example a light beam is able to transmit the whole encyclopedia Britannica within one second (Röthlein 1999). To lose no speed it is reasonable to use electric devices as rare as possible because every electric communication device is a potential bottleneck. At the beginning of the development a full optical computer will not be possible. Many devices will still work electrical. Even after a lot of development electronic parts most likely will still remain in optical computers, e.g. for instruction and controlling tasks.

Higher Parallelism

There are two options to achieve higher parallelism in computers (Linderman et al 2008) One is to increase the amount of data which is sent through bus systems and computed in the CPU at each time. Modern conventional computers and operating systems base on 32 bit or 64 bit architecture. Often application software only supports 32 bit systems so the software does not take full advantage of 64 bit systems. Optical computers can be built with higher bandwidth. Within one data path several data sets can be transmitted parallel at the same time using different wavelengths or polarizations. But thereby attention to interference is necessary. Due to the coherent laser light destructive interference depending on the phase might occur. The higher parallelism and the superior velocity of light allow extreme processing speeds. But to take full advantage of this new architecture operating systems and application software have to be adjusted to it.

Furthermore data paths are able to cross each other without interference. This advantage of optical technologies can help to build architectures and layouts with superior parallelism. New layouts can be more three-dimensional and thus the space in a computer case can be used more intensively. With adequate miniaturization of optical components the size of computers could shrink.

Conventional computer technology is based on electric current and electrons. While electric current is very fast, the average drift velocity of electrons is rather slow. In reality there is nothing faster than the speed of light. This makes light and photons to the perfect information carrier. Even long distances can be bridged within split seconds.

Less Consumption

Current computers consume a lot of energy. Modern CPUs often need over 80 watts in idle state, around 120 watts in normal use and up to 250 watts in performance mode Golem and Meisterkühler (2007). For complex visualization a high performance graphics card is needed which needs up to 150 watts itself. The computer industry realized that issue several years ago. Today especially for notebooks energy-saving components are built.

Less heat is released

Less heat is indeed released using light. Sounds contradictory since light sources radiate heat. But in optical computers lasers are used as light sources. Those concentrated light beams only consist of a small spectrum of different wavelengths. Depending on the field of application lasers that have different needs of energy and produce heat to a greater or lesser extent. Most modern CPUs are not able to work without a proper airing. The reason for that is the friction of the electrons in the integrated circuits. Those moving electrons hit each other within wires and ICs and thus heat is generated. Airing a processor (whether it is a CPU, GPU or the like) or the whole case needs energy, space and produces noise. Optical computers could be smaller because there is no need for a fan or free spaces for air circulation. Big computer centers with thousands of computers need powerful air conditioning systems. These aggregates are expensive and need a lot of energy too. Besides that the released heat increases the danger of fire at computer centers.

Less Noise

Conventional computers often cause a lot of noise due to rotating fans and drives. High speed processors accelerated to their architectural limits need enormous active and passive cooling. In the past small fast spinning fans often were used which created plenty noise. Some years ago the computer industry realized the problem of the annoying noise and developed fans with bigger size. Thus the same volume flow was established with a lower rotary speed and the noise development was reduced.

More flexibility in layout

Conventional PCs are built as a rectangular box (desktop) or as a laptop. One reason for that is the speed of electronic connections. It depends on the length of the cables and pipelines. On the motherboard the CPU, RAM and graphics card have to be close to each other to be able to move huge amounts of information. Longer distances imply the decrease of the practical transfer rate. So the optical computer technology has the potential to change the shape and layout of computers fundamentally (Ambs 2010). The components of one computer can be spread across a car, a building or even a city with almost no loss in performance. Consequently the server/client and the peer-to-peer architectures could be advanced. Many clients, terminals or even single components can be connected optically and consequently allow higher ranges

Less loss in communication

Today communication often is realized with electric wires or wireless by radio frequency. The ranges of those communication ways are limited. Data sent through wires needs to be amplified several times to bridge longer distances. The communication with optical fibers is almost lossless due to the total internal reflection (Brown 2011). So amplifying the signal is not or only rarely needed. Furthermore a higher bandwidth is possible, optical communication is insensible to electromagnetic interfering fields and it is more tap-proof. For high performance communication (e.g. for backbones) already today fiber optics are used (Ambs 2010).

Less Wear

Wear normally occurs at mechanically moving parts. In conventional computers those parts are especially fans, hard disk drives and conventional optical removable storages (CD, DVD, HD-DVD, Blu-ray disks). All those components have in common that they rotate or move very fast and thus friction is caused. Because of this friction the mechanical parts wear out and break. As already mentioned, this friction causes heat which is suboptimal, too.

In optical computers fans possibly will not be needed any more. An optical processor does not heat up due to internal friction of the electrons like a conventional does. Additionally new technologies for mass storages can be established. Saving in the form of holograms or on molecular basis is possible. Those forms do not need fast spinning parts and do not wear out so heavily (Biancardo et al 2005).

Drawbacks

Optical computers are only prototypes and do not reflect the whole capabilities of optical computing (Woods and Naughton 2008). Consequently, many of the disadvantages of optical computing are not because of the principle of the new technology itself but because of contemporary production technologies. The machines and processes that could be used to manufacture optical computers in mass production are still in its early stages. The following are the disadvantages of optical computers compared to conventional computers according to Knight (2012):

Optical components and their production is still expensive

Conventional ICs are produced in high tech factories whose sole task is to manufacture ICs. Since the specialization and productivity of those factories is rather high the price of the product is low. Experts say the price of one transistor matches approximately the price of a printed character in a newspaper. Earlier the price was a lot higher but due to new abilities in manufacturing and the new factories it decreased.

Optical components are not miniaturized enough yet

Existing modern IC processors are built in a very high density called VLSI (very-large-scale-integration) or ULSI (ultra-large-scale-integration). There are several millions of transistors in an area of only approximately some square millimeters. The size of the transistors still decreases and some parts of the transistors already reach atomic dimensions.

In contrast to that optical components can be made small and compact but not really miniaturized. The area of optics ranges from macrooptics over miniature optics to microoptic(Quick 20011). Unfortunately there are no microoptic integrated circuits specifically developed to assemble a CPU or a motherboard yet. A lot of development and new processes will be needed (Ibrahim et al 2004)

Problems of exact manufacturing

Today conventional processors and computer components are manufactured with high precision and in huge charges using robust processes. Manufacturing problems can be eliminated by proper quality assurance. A change from the existing assembly method concerning the size of the chip structure to another size or using bigger wavers can trigger problems. For instance AMD recently had some problems changing their production from 90nm to 65nm structure.

Miniaturized optical components have to be built very exactly to work properly. This exactness often is not reached yet. Small deviations can cause massive problems diverting light beams. Exact production is expensive which leads to the next disadvantage.

New expensive high-tech factories have to be built

An IC factory costs several millions up to billions of dollars. Chip manufactures do not want to close such factories due to the high investments unless they have amortized. So the goal of the chip manufactures is to integrate optical components into the existing concepts and create hybrid devices. To allow integration optical devices have to be adapted and are not able to show their whole capabilities using an all optical architecture. So at first the integrated optical components will probably be produced in existing IC factories. Later own factories can be built to produce sole optical parts (Jackson 2011).

Incompatibility

Modern Personal Computers (PCs) are put together according to the Von Neumann architecture. Application software and especially operating systems are programmed to match this architecture. Because of these existing standards most of the application software can be used on any computer using a Microsoft Windows operating system. The portability is rather high.

Optical computers may use a different architecture particularly regarding the parallelism of the system. Conventional existing computer programs working sequentially will have to run emulated in a kind of compatibility mode. So these programs cannot use the full calculating speed of optical computers or even worse some programs might not even work. Here the question arises whether the software drives the hardware or the hardware drives the software. Concerning optical computers the software will depend on the new architecture of the hardware. Software especially programmed for optical computers probably might work on conventional computers. The two different architectures existing next to each other with incompatible software is the worst scenario. Then, software can only be used on an architecture so that the portability and capability is quite low.

The two problems that are significant in optical computing are: the need to transition between optic and electric; and size and power requirement of short distance optical transmission (Quick 2011). It is noteworthy that Software especially programmed for optical computers probably might work on conventional computers.

Conclusion and Recommendation for Further Studies

There are numerous applications for digital optical processing. As with any new technology, the technology is developed with a certain application in mind, while that technology may be used in the future for things unimaginable. Three applications which are relevant to the current time are digital computers that are purely optical, optical interconnects between electronic chips, and photonic neural networks.

The dream in designing optical diodes and transistors is a purely optical digital computing system. Current electronic computers are reaching limits on size and speed. Optical computers hold the promise of high bandwidth, high speed processing that is unattainable with electronic computers.

The future of optical computing is very bright. Much research is being conducted in many areas in the field and many discoveries are being made. The main promise of optical computers is speed and bandwidth. Taking the conversion from electron to photon out of the equation greatly reduces transit time for data. All optical system may have the ability to process data in ways that are currently unimaginable. Though, it will be a long time before photons replace electrons as the main medium for processing data. It is therefore recommended that future research should concentrate on all factors that are considered as disadvantageous to optical computing so that all applications that involve optical computing can be developed to surmount present and future challenges.

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