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RESEARCH ARTICLE

"PHOTONIC INTEGRATED CIRCUITS: GIANT LEAP IN COMPUTING TECHNOLOGY"

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Abstract

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There is a continued demand for increase in computing requirements from sensor, smartphones, to servers. However, the technology improvements in clock speed, power, and memory bandwidth from traditional electronic integrated circuits (EIC) has started to saturate. This has triggered further research in exploration of photon integrated circuits (PIC) that utilize photons (or particles of light) as opposed to electrons to form a functioning circuit. Research suggests that by integrating the benefits of EIC and PIC, one is able to harness the best of both worlds. The inherent advantages of photonics technology such as speed, energy-efficiency, and density, coupled with the advances in material technology, make them suitable to address the challenge of designing heterogeneous chips. This paper presents the fundamentals of the photonic technology, applicability to solving digital computing problems, ability to integrate into PICs, and its capability to complement electronic integrated circuits for powering the computing demands of emerging applications.

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Introduction:-

Integrated electronics and integrated circuits (IC) have had a significant impact on every aspect of human life. It is hard to imagine a life without ICs today. The influence has been so phenomenal that there is still an insatiable desire for increasing energy-efficient computing performance. Industry survey indicates that the total internet demand continues to grow by 40% per year[1]. With the advent of emerging technologies such as Artificial Intelligence, improved device capabilities, and penetration of technologies into emerging markets, the appetite for data driven services is expected to continue as shown in Figure 1 below.

For the last 60 years, Moore's Law[2] has been the guiding principle in the semiconductor industry to improve computing performance. Moore's Law[2] states that the number of transistors on an integrated circuit will double every two years with minimal rise in cost. This enables increasing the 'clock speed' as well as 'pack' more functionality in a smaller area.

'Clock Speed' is a measure of the number of cycles the CPU executes per second, measured in Gigahertz (GHz). A "cycle" is the basic unit that measures the CPU's speed. During each cycle, billions of transistors within the processor open and close. If we look at the trend for clock speeds for CPUs over the past 10-20 years, we observe that the improvements in clock speed of the newer CPUs are not seeing improvements in line with Moore's law. From Figure 2below we see that the clock speed has reached a plateau since year 2000 although the number of

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transistors should have increased as per Moore's law, thereby showing us that the speed of computing by the use of transistors in the IC of the CPU has saturated.

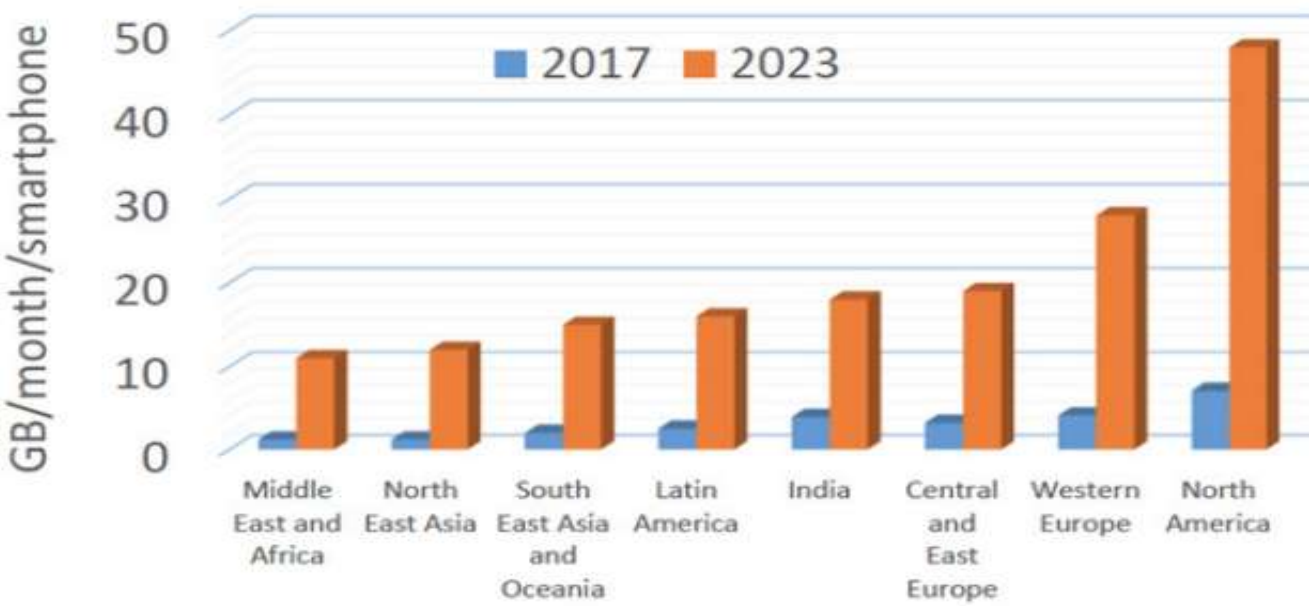

Fig. 1. Data traffic pre active smartphones in Gigabytes per

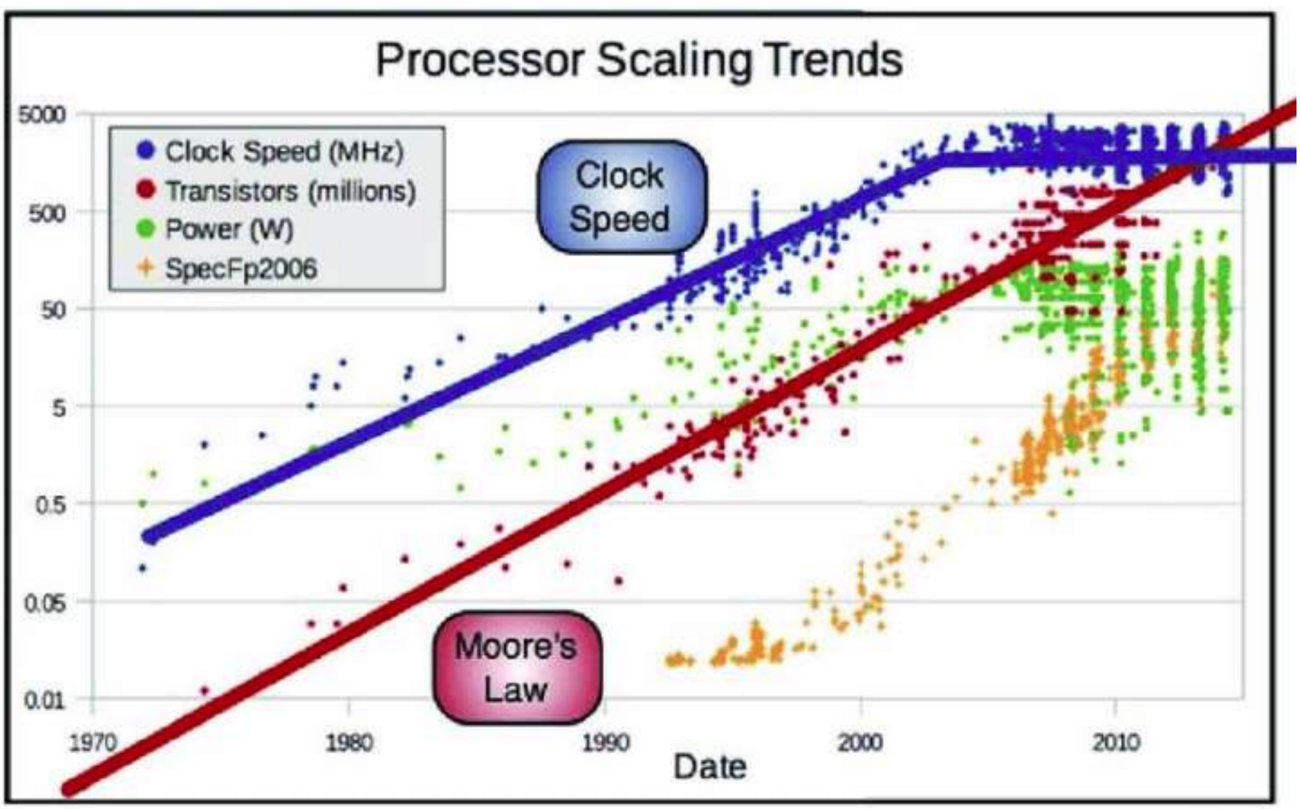

Figure 2:- The use of conventional electronics as we know it has reached its limit of computing speed. This paper delves into the application of photonic technology to increase the clock speed of the CPUs.

The paper suggests that traditional electronics that has played a key role in the manufacturing and use of ICs today could be complemented with Photonic ICs to overcome the problem of stagnant clock speed of the CPUs. The paper first explains the traditional electronic materials and processes in use today and then goes on to explore photonic integrated circuits (PIC) technology as an approach to complement existing EICs.

Electronic Integrated Circuits (EIC)

EICs are primarily constructed using semiconductor materials such as silicon[3] due to their properties that allow for precise control of electrical conductivity. Semiconductor devices rely on the ability to manipulate the flow of electrons through the material, achieved by doping with impurities to create n-type (electron-rich) and p-type (hole-rich) regions.

Semiconductor material can be classified into two major types: intrinsic and extrinsic. An intrinsic semiconductor is 100% pure, while extrinsic semiconductors have added impurities. The adding of impurities to semiconductors, called doping, greatly enhances the conductivity behaviour of the material. A 100% pure semiconductor is tetravalent in nature. This means that the atoms itself have 4 valence electrons, and upon making 4 covalent bonds with 4 other neighbouring atoms, they obtain a very stable octet structure. In the case of extrinsic semiconductors, there are added impurities. These include atoms that are trivalent or pentavalent in nature.

When a trivalent atom is added to a 100% pure sample of silicon, it results in a structure which has 7 valence electrons after covalent bonding. The space where the 8^{th} electron should have been is empty, and called a ‘hole’. This is a positive-type semiconductor, or a p-type semiconductor. When a pentavalent atom is added to a sample of pure silicon, it results in a structure which has 9 valence electrons. However, this exceeds the capacity of the energy level, resulting in the 9^{th} electron becoming delocalised. This is a negative-type semiconductor, or a n-type semiconductor. These ‘holes’ and free electrons greatly enhance the flow of charge and hence increases conductivity. In electronics, Bipolar Junction Transistors (BJTs) are of two types: n-p-n and p-n-p.

Transistors have two main uses: as a switch and as an amplifier. The diagram below shows the mechanism for the transistor acting as a switch.

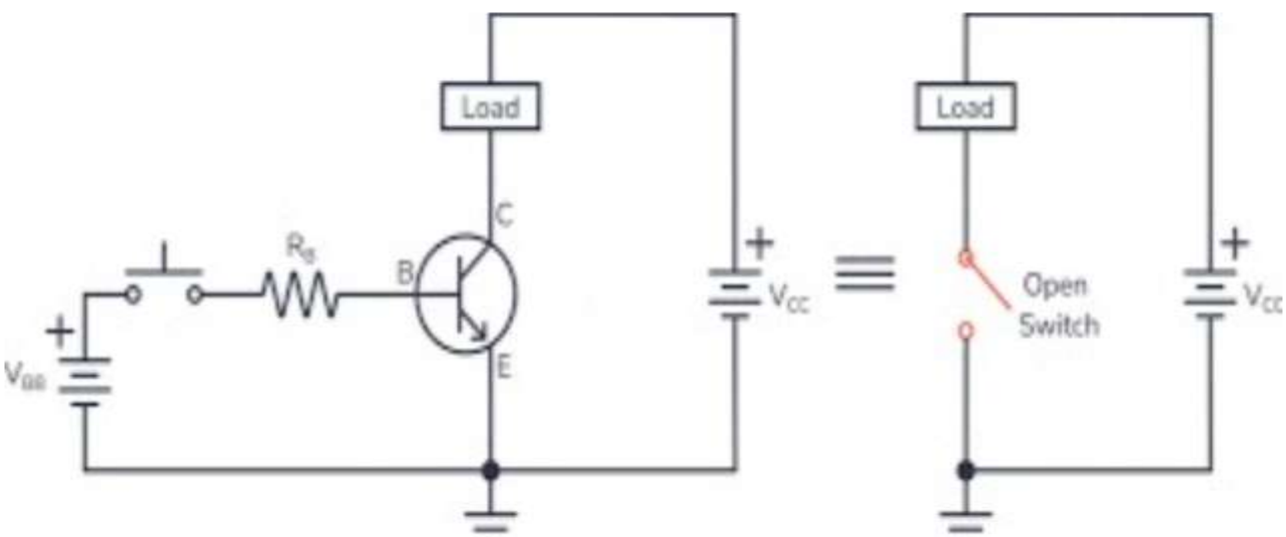

Figure 3:- Transistor as a switch.

The base and the emitter are always in forward bias (as indicated by the arrow head). The EMF of the cell Vbb causes a current to flow clockwise to the Base (B). This current subsequently flows to the n-doped emitter (E) as shown by the purple arrow. Another cell Vcc causes a current to flow anticlockwise to the collector (C). Since originally C and B are in reverse bias, we now need to force the current to flow from C to B. Hence, Vcc has a higher Electromotive force (EMF) than Vbb so that the potential at C is higher than the potential at B, causing current to flow from C to B. If the voltage at B does not cross a certain specific voltage, the transistor will not conduct electricity. So, the current in the ‘Vcc circuit’ will also cease. This voltage is known as the threshold voltage and this mechanism enables the transistor to act as a switch.

This mechanism of transistors acting as a switch is vital to the functioning of the CPU. ICs, especially CPUs, integrate billions of transistors onto a single chip, interconnected through multiple metal layers. Interconnects are crucial as they carry signals between different parts of the circuit, enabling functionality and data processing. The functionality of an IC depends on its design and the arrangement of transistors and other components. Digital ICs process binary data (0s and 1s), using logic gates (AND, OR, NOT, XOR) constructed from transistors.

Electronic Logic Gates

A logic gate is a device performing a Boolean logic operation that process one or more binary inputs and provides a single binary output. Logic gates are devices that act as building blocks for digital circuits. They perform basic logical functions that are fundamental to digital circuits. The fundamental logic gates are categorized into seven types: AND, OR, XOR, NAND, NOR, XNOR and NOT.

Connecting two transistors in series makes them act as insulators. Only when both transistors act as conductors (both input values are 1, and a voltage is applied to both bases) will the output be 1 (current on the right-hand side). This is a simple AND gate. The output is determined by the arrangement of the transistors.

Similarly, if we connect two transistors in parallel, we do not necessarily need both transistors to act as conductors to get an output of 1. Since it is a parallel arrangement, even if one transistor acts as a conductor (i.e. voltage is applied to the base of any one transistor), there will be a current on the right-hand side, corresponding to an output value of 1.

The connecting of transistors in series and parallel to respectively create an AND & OR gate is illustrated in Figure 4 below.

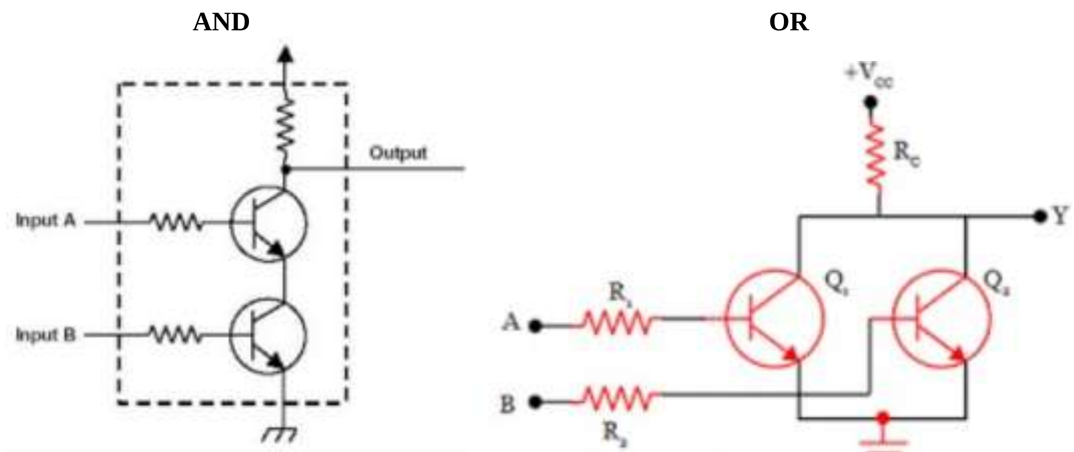

Figure 4:- In reality, digital ICs are highly complex, and one often needs to use a combination of logic gates to achieve the desired logic functionality.

Photonic Integrated Circuit (PIC)

Even though the systems explained above are highly sophisticated, we seem to have reached the limits of clock speed improvements of EICs. Use of fibre optic cables globally has revolutionized the speed of telecommunication. Optic fibre has replaced the traditional copper wires over which signals used to be transmitted. Taking a cue, researchers have proposed that it would be possible to investigate the development of ICs that are based on photons instead of electrons. This could significantly increase the processing speed of CPUs. The following section delves into the physics and technology of photons, and what makes it possible to use them for computing in a Photonic Integrated Circuit (PIC).

Photons are particles of light that exhibit wave-like properties. They travel at the speed of light in vacuum and can carry information encoded in their frequency, phase, and polarization. A Photonic Integrated Circuit (PIC) is a chip that contains photonic components, which are, components that work with photons (light). An electric current flows at only 10 percent of the speed of light. This limits the rate at which data can be exchanged over long distances. By applying some of the advantages of visible and/or Infra-Red (IR) networks at the device and component scale, a computer might someday be developed that can perform operation orders of magnitude faster than a conventional electronic computer.

The 'photonic concept' isn't exactly new. Photonic ICs have been developed for more than 30 years, primarily driven by communications technology[4]. In fact, most of us make use of it every day. Internet Service Providers use optical fibres/optical links to transmit data at high speeds and efficiently. This enables us to enjoy high internet speeds.

A simple scheme that comprises of the following, could help achieve speeds of 100 Gbps:
1. A light source (for example a laser)
2. A modulator to encode a signal onto the beam of light. This is done by modulating the phase, the amplitude or the polarization of the light.
3. A transmission medium
4. A photo detector, to detect the signal at the other end

To 'replicate' this in an EIC, a major problem with light needs to be overcome. Light tends to always travel in a straight line, making it tough to 'trap' and guide. To do this, a principle called total internal reflection is used. A material with a higher Refractive Index (RI) tends to 'bend' or refract the light at a greater angle, than those with a lower RI. If we can create such a system that does not absorb light (to prevent loss) but greatly reflects it, we can successfully 'trap' or 'confine' the light beam. This is achieved by taking a tube made of a material with a very high RI and then surrounding it with a material with a very low RI. This system can now be used to guide the light, and hence is called a wave guide. To scale this down to a chip-level arrangement would greatly increase efficiency, reduce power consumption, enable bulk production and much more.

To achieve this, it is essential to implement all the core functions on the surface of a chip. These include transporting light, filtering wavelengths, signal modulation and signal detection. To transport light, first a strip of high RI surrounded by a strip of low RI, that can confine the light, are defined so that it can be guided as desired. This is very similar to the concept of an optical fibre on a planar surface. We can also 'split' the light beam by coupling two wave guides very close together side-by-side which is called a directional coupler. This can also be done by a 2x2 coupler.

Now, to tackle wavelength filtering, optical ring resonators are used.

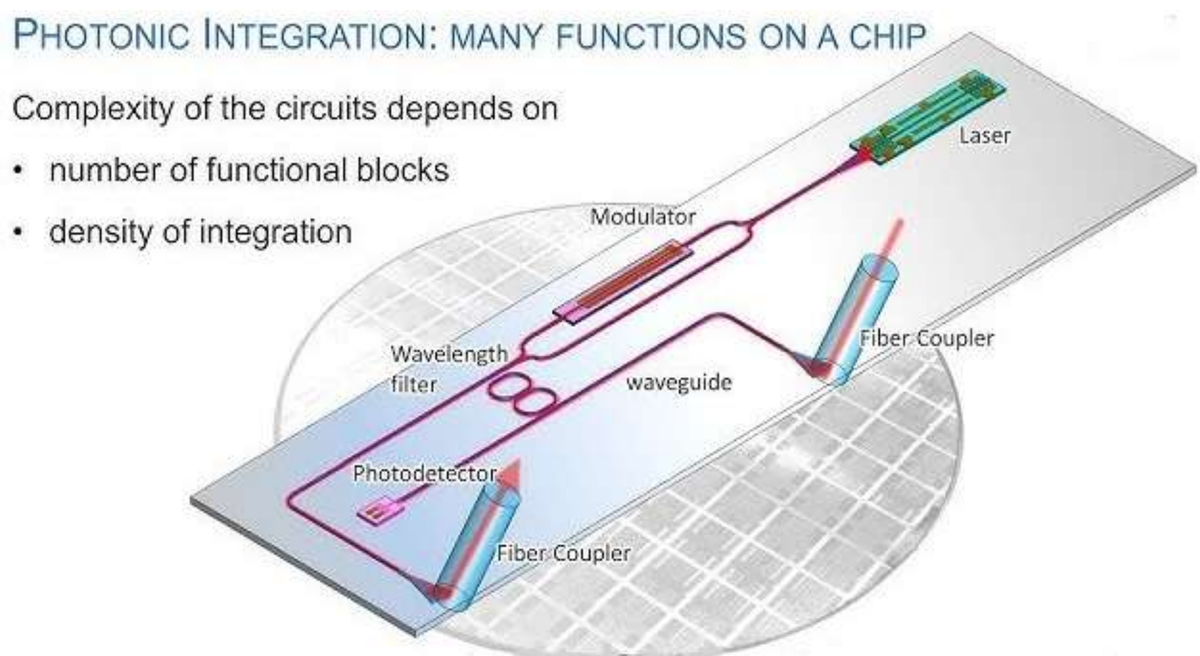

Figure 5:-

The light is initially travelling through the wave guide. It then encounters a coupling mechanism as discussed above, and splits into two parts. However, not all wavelengths of light enter the ring. Only those wavelengths that are smaller than the cross-section of the ring will be able to pass through, and undergo the circular motion. For these specific wavelengths, the light is coupled out into the output through the other side of the ring resonator; while the other wavelengths of light simple pass through the original wave guide path.

In order to encode information onto a light beam the electrical signal needs to be converted into an optical signal. This is achieved by an electro-optic modulator. It takes an electrical signal and an unmodulated, continuous beam of light to output a signal imprinted onto the beam of light. This imprinting can be based on several physical mechanisms such as temperature, presence of electrical carriers and intrinsic electro-optic effects of the material. To translate the optical signal back to an electrical signal, a photo detector is used. The incident photons (modulated light) are converted into an electrical current.

Finally, some sort of light source is needed. This is achieved by using a laser. Unlike most electronics which are made from silicon, PICs use a wide variety of materials. For instance, to make a laser, we can use III-V semiconductors because these have a direct band gap that are extremely good at emitting light.The figure 5 above depicts the working of the entire PIC.

Photonic Logic Gates

Now that we have successfully been able to 'manipulate' light at the chip level, we can carry out several operations using photons and create logic circuits similar to electronic logic gates. A photonic logic gate processes inputs in the form of light pulses and produces an output based on the rules of Boolean logic (AND, OR, NOT, etc.). Unlike electronic gates that use electrical voltage levels, photonic gates manipulate the properties of light waves to achieve similar logic functions.

To replicate electronic gates, the ability to control both light inputs into the gate is needed. This can be done by the simple use of the phenomena of interference. Wave interference is the phenomenon where two or more waves superpose to form a resultant wave. The resultant displacement at any point is the algebraic sum of displacements of the individual waves. For the light source a coherent monochromatic beam such as a diode laser can be used. The ray can then be passed through a slit which divides it into two parts, I1 and I2. It is important that each input, I1 and I2, can be controlled separately.

Now, let us delve into how to construct some basic logic gates using optical interference. In Figure 6 below, A and B are switchable coherent light beams. In this case, both beams are kept in phase with each other resulting in constructive interference at the plane below. When both beams are kept on, in phase, there is constructive interference at the plane below, resulting in a '1' output. Even when either beam is kept on there is light passing through the hole in the plane, indicating a '1' output. This is a simple OR gate.

We can change the phase of one of the beams in order to force destructive interference at the plane below. If we make the phase difference between the two waves to be 180degrees, then we will have constructive interference if both beams are switched on. There will be light passing through the plane below only if either beam is turned on. This is an Exclusive OR gate (EOR).

Now, instead of two beams that can be controlled individually, a third beam can be added that is kept on. This beam could be out of phase with the initial I1 and I2 beams. Only when both beams are turned on light will pass through the plane, corresponding to a '1' output. Otherwise, destructive interference will occur and there will be a 0 output. This is an Exclusive NOR gate (ENOR).

By using this phenomenon of interference, it is possible to construct any combination of logic gates.

Advantages

Electronic circuits, due to resistive losses and capacitive charging/discharging, result in a huge amount of energy dissipation in the form of heat. Photonic circuits do not face this problem because photons, unlike electrons, do not face any resistance. As a result, their **energy consumption** while transmitting data or processing is significantly lower. In-chip and inter-chip photonic interconnects could drastically bring down the power needed to communicate between chips and within data centers and hence result in overall energy savings.

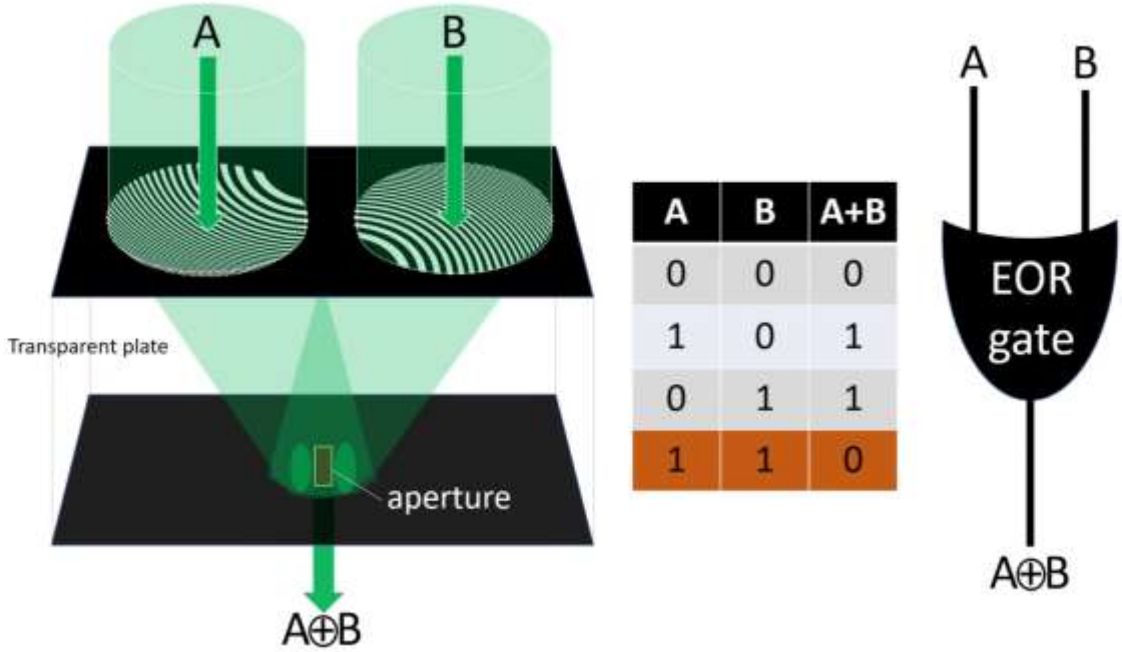

Figure 6:-

Photonic processors take **computing speeds** to the next level where computation happens at the speed of light, and allows significant improvements in real data transfer rates and computational speeds. Photons are the basic quandary of light and therefore are really fast as compared to electrons in a conductor. For this reason, this intrinsic property makes photonic circuits achieve **data transmission rates** in the Tera Bits-per-second magnitude, far exceeding those by electronic circuits in the Giga Bits-per-second range. The intrinsic bandwidth of optical fibre is very large and it can support many wavelengths of lights simultaneously.

Heat generation is a major concern in electronic processors, often requiring complex cooling solutions to prevent overheating and ensure reliable operation. Photonic processors generate much lower heat due to their lower energy dissipation. This not only reduces the need for cooling infrastructure but also allows for denser packing of components, potentially leading to more compact and efficient computing systems.

Photonic circuits are capable of achieving **extremely low latency** because light is able to propagate through optical fibers or wave guides virtually without any delay. This is very important in high performance computing (HPC), and real-time processing, where fast data exchange with as little delay as possible are crucial. Thus, photonic integrated circuits are able to effectively minimize the latency of communications between different parts of a processor or several processors in a distributed system.

Photonic systems are very good at carrying out **multiplexing techniques**, especially Wavelength Division Multiplexing, which offers the possibility of sending many data channels simultaneously on different wavelengths of light along the same optical fibre. This significantly increases the data-carrying capacity for optical networks and processors; allowing for better use of the available bandwidth available and thus avoiding the extra physical infrastructure.

Opportunities

In the recent decade, there has been tremendous activity in silicon photonics. Silicon PICs enable high-performance, complex systems for communications but are limited in wavelength and lack on-chip sources[4]. There has been a lot of research to integrate multiple material and moving from pluggable to on-chip optics. While communications is a well-established market, there are many other emerging markets that would benefit from improvements in design, cost reduction and power consumption. The applications include virtual reality, quantum computing, sensing, positioning, Radio Frequency (RF) systems, healthcare, etc.

The ability to fabricate a complete optical system on a chip offers wide advantages such as cost, weight and power efficiency[5]. Co-packaged optics is an inter-disciplinary approach that optimizes and packages electronics and photonics into one body[6]. On-chip light source integration is being explored under this option as depicted in Figure 7 below.

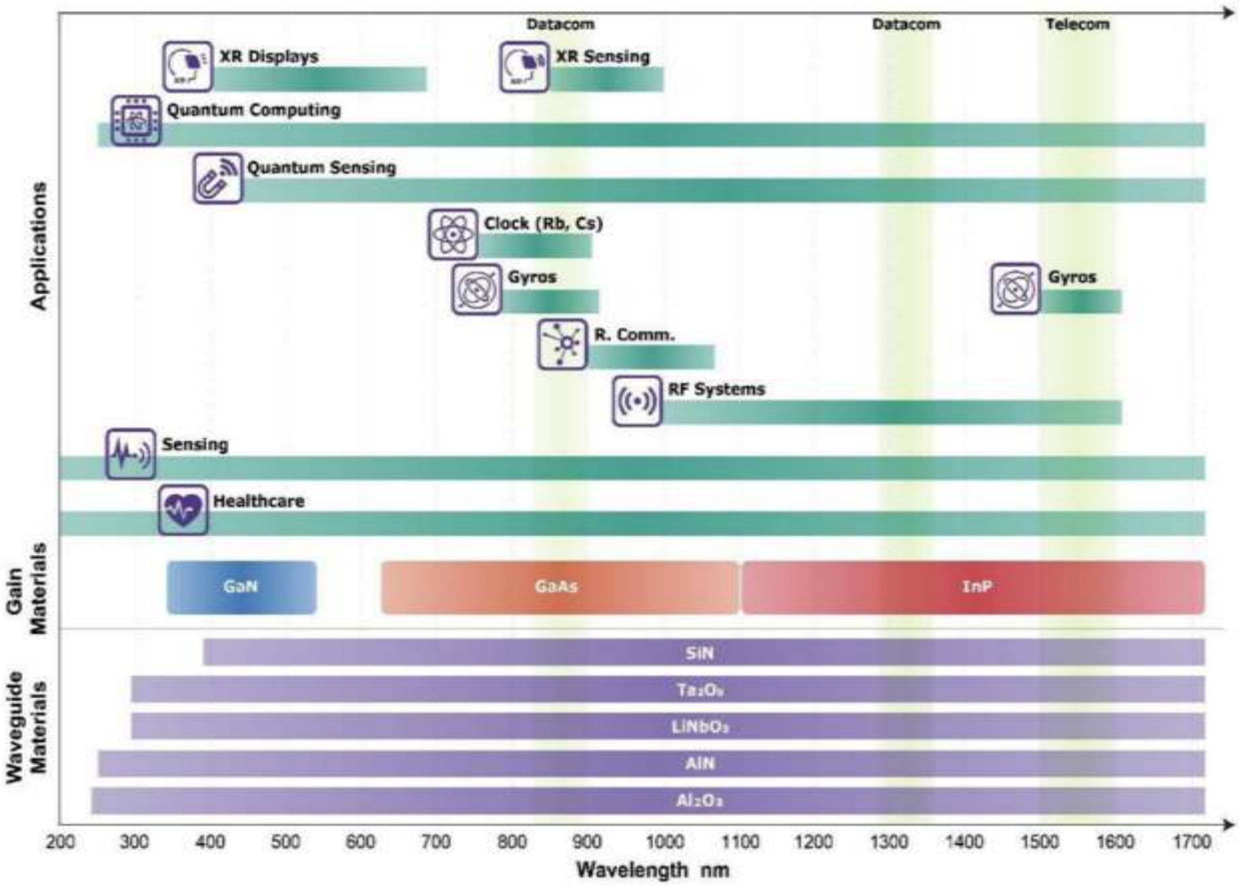

Figure 7:-

Challenges

The lack of interoperability with the old integrated circuit design tools makes the combination of electronic-photonic co-design challenging. Data and telecom industries have very clear technical requirements, and optical fibre was the main driver which clearly defined the wavelength of operations. The markets for these technologies is large and thus significant amount of money was pumped into these sectors. However, the emerging sectors may have different requirements and may not benefit from the same scale of investments.

Inter disciplinary research and collaboration between material development groups, PIC groups and consumer groups is needed to accelerate commercial scaling. Experience from the telecom and data sectors could be used to accelerate development of heterogeneous photonics.

Conclusion:-

Photonic processors and chips provide a breakthrough complement to conventional electronic systems, and promise huge improvements in computing performance, efficiency, and capability. As traditional electronics reaches its limits (saturation in clock speed improvements and high energy consumption) the future lies in photonic technologies. This is because of the ability of photonic ICs to exploit the intrinsic advantages of light: ultra-high speed in data transmission, vast bandwidth, and low energy dissipation, all of which greatly improve computational speed and efficiency.

Photonic ICs pave the way towards a scalable and complex integration, and design of sophisticated systems that are able to host a diversity of functions on one chip alone. Their operation could exploit all multiplexing techniques to further amplify data throughput, thus catering to modern applications. Very high frequency operation, combined with huge bandwidth density, could give photonic circuits an edge to lead in the future revolution in telecommunication and high-performance computing.

Transitioning from electronic to photonic integrated circuits is a giant leap in computing technologies. With the integration of photonic components in the CPU, it could complement the current limitations of electronic ICs, alleviate bottlenecks, and offer a strong and sustainable solution to power future computing demands.

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