Photonic Quantum Computer
(Optical Quantum Computer)

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***Abstract*- Computer is a simple logic device consisting of 2 bit logic called Logic Gates. These logic gates constitute to make circuits, and these circuits constitute to make communication systems. Basically a computer follows the laws of Newtonian Physics or Mechanics. But due to advancements in technology, the size is shrinking day by day and maintaining these laws of physics are getting tougher. So, Quantum Physics or Mechanics are introduced to maintain the next generation computation technologies. Quantum mechanics is a fundamental theory in physics that provides a description of the physical properties of nature at the scale of atoms and subatomic particles.This quantum mechanics is used to compute data, called as quantum computing. Unlike normal computers that we use in our day to day life, Quantum Computers are different in terms of size, speed, storage, and many other aspects.QuantumComputingistheuseof quantum phenomenon like superpositionandentanglement to perform computation of data. Photonic computing and Quantum computing are merged together to create Photonic Quantum Computers.**

Keywords*- *Computing, Optical Computer, Photonic Computing, Quantum Computing, Photonic Quantum Computer

I. INTRODUCTION

Computer generation began in the late 1950s, when digital machines using transistors became commercially available. In this traditional approach to computing, information is stored in bits, that are represented logically as either a **0**(off) or a **1**(on).

Advancements in the computing technologies introduced optical or photonic computing. Optical or photonic computing uses photons produced by lasers or diodes for computation. For decades, photons have promised to allow a higher bandwidth than the electrons used in conventional or classical computers.

Just like classical and optical or photonic computers, quantum computers are also introduced. Unlike classical and optical computers, quantum computer uses **1s** and **0s** as bits and also uses a 3rd bit that allows them to represent **1** or **0** at the same time.

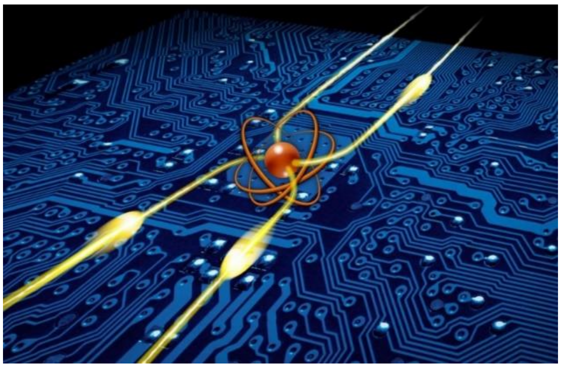

Fig. 1. Concept design of a Quantum Computing System

II. HOW SMALL CAN A TRANSISTOR BE?

Transistors have been in use since the 1940s in different machines. Digital machines started using transistors in the late 1950s and since then the computer generation began and were commercially available.

A basic computer has a circuit chip (processor) which has basic modules and these basic modules include logic gates. These logic gates are made up of millions or billions of switches (transistors) which passes or stops the flow of electricity to store data.

These transistors are made up of Silicon, the 2nd most abundant material found on Earth. Since 1950 – 2020 these transistors have evolved and along with that evolved the computers. From **10,000nm** to **7nm**, the size of the transistors kept on decreasing and it's still decreasing. A basic transistor used in the processor is of **14nm**, which is 14 times wider than a DNA molecule.Decreasing it's size more will lead it to the size of a single atom, in that case transistors can't act as a switch.

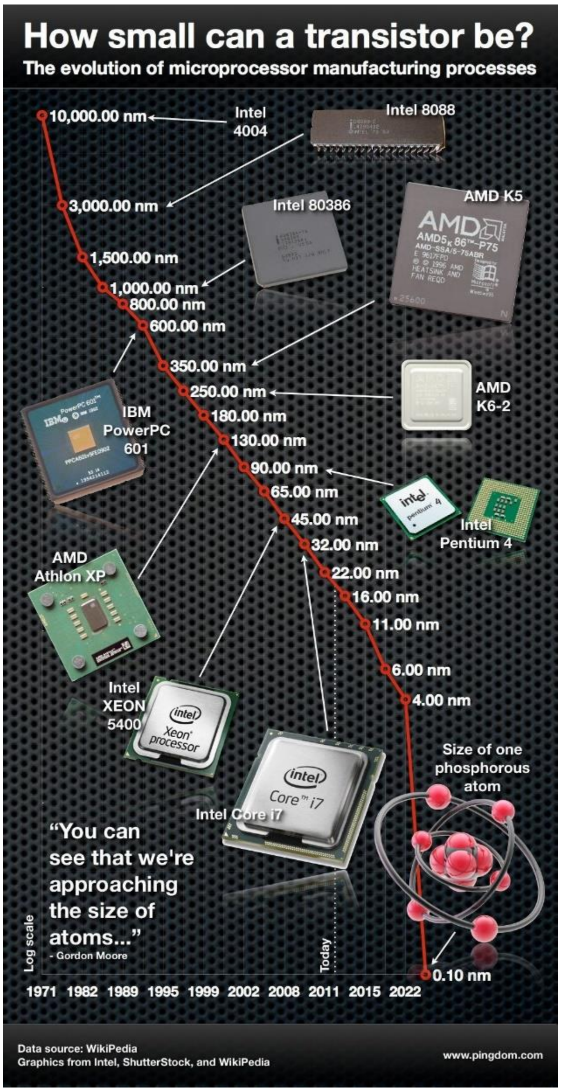

Fig. 2. Evolution of Transistors and Processors

III. FUTURE OF COMPUTING

From Classical Computers to Super-computers to Optical or Photonic Computers to Quantum Computers, computing technology evolved. The size of processors is decreasing, which leads to more efficiency, speed and less power consumption. Since the size is getting smaller, it's getting close to the size of a single atom, in which case the electrons can't be stopped for use. This phenomenon in which the electrons move through the transistors without stopping is called "Quantum Tunnelling". It happens when the size of transistor is equal to the size of atom. To overcome this, Quantum Computers and Optical Computers are built.

Most research projects focus on replacing current computer components with optical equivalents. This approach appears to offer the best short-term prospects for commercial optical computing. For this, electronic transistors are replaced with optical transistors.

Now in case of Quantum Computers, they are believed to be able to quickly solve certain problems that no classical computer could solve in any feasible amount of time—a feat known as "Quantum Supremacy".

Fig. 3. Future of Computing

IV. CLASSICAL BITS VS QUANTUM BITS

Classical Computers uses Bits, **0** (off/low) or **1** (on/high) to represent information logically. Byte is the unit of information storage (**1 Byte = 8 Bits**). 1 Byte is enough to hold 1 typed character like 'b', 'X', '$' etc. All storage is measured in bytes, despite being very different hardware.

Classical Bits have only 2 states (on/off) – **0, 1** which are mutually exclusive. In Classical Bits **0** represents low charge and **1** represents high charge. The combination of bits is limited.

The quantum equivalent of a Classical Bit is called Qubit, which is a two-state quantum mechanical object used in quantum computing. The combination of Qubits is unlimited, because Qubits can't be defined until the value is measured. A Qubit has 2 states, **0** and **1** and a 3rd state which represents **0** or **1**at the same time (**2^n = 1 Qubit**). Qubits have 2 states (**Ket 0, Ket 1:|0>, |1>**) and they show Superposition of both states and Quantum Entanglement together. To attain or maintain this quantum supremacy, Qubits are kept at low temperatures (0^oK) with magnetic fields.

In a Pure Qubit State, $\psi = a|0\rangle + b|1\rangle$ where a, b are complex variables such that $\sqrt{|a|^2 + |b|^2} = 1$. Therefore, there are 8 possible states per bit.

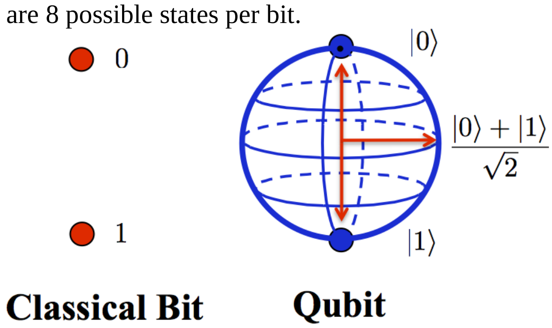

Fig. 4. Classical Bit vs Quantum Bit

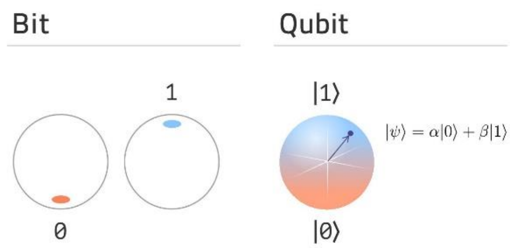

Fig. 5. States of Bit

V. QUANTUM CIRCUITS

The Qubits form quantum gates and these quantum gates together form Quantum Circuits. A memory consisting of n bits of information has $\mathbf{2^n}$possiblestates.We begin by considering a simple memory consisting of only one bit,

$$|0>: = \begin{pmatrix} 1 \\ 0 \end{pmatrix}; \quad |1>: = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

A quantum memory may then be found in any quantum superposition of the two classical states**|0>** and**|1>**,

$$|\psi>: = \alpha|0> + \beta|1> = \begin{pmatrix} \alpha \\ \beta \end{pmatrix}; \quad |\alpha|^2 + |\beta|^2 = 1$$

The coefficients **α**and**β** are complex numbers, whereas the numbers **α** and **β** are called quantum amplitudes.

One important gate for both classical and quantum computation is the **NOT** gate. For 1 Qubit memory,

$$X: = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

X|0> = |1> and X|1> = |0>

The possible states of a two-qubit quantum memory are,

$$|00>: = \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix}; \quad |01>: = \begin{pmatrix} 0 \\ 1 \\ 0 \\ 0 \end{pmatrix}; \quad |10>: = \begin{pmatrix} 0 \\ 0 \\ 1 \\ 0 \end{pmatrix};$$

$$|11>: = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 1 \end{pmatrix}$$

$$CNOT: = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix}$$

CNOT|00> = |00>; CNOT|01> = |01>;
CNOT|10> = |11>; CNOT|11> = |10>

Most quantum circuits depict a network consisting only of quantum logic gates and no measurements.

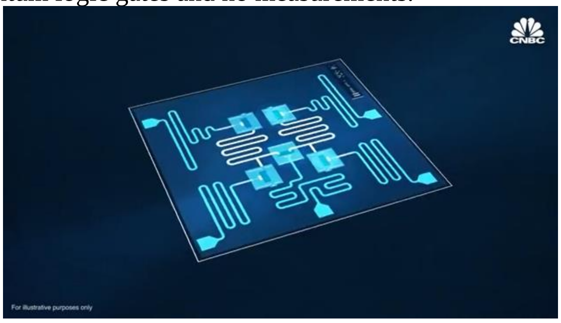

Fig. 6. Quantum Circuit

VI. QUANTUM COMPUTERS

Qubit is the main building block of Quantum Computation. Quantum Computing is the use of quantum phenomenon like Superposition and Entanglement for computation.

Quantum Superposition states that any two or more-quantum states can be added together and the result will be another valid quantum state.

Quantum Entanglement states that the quantum state of any two or group of particles separated by a large distance cannot be described independently of the state of the other.

Quantum physics describes the behaviour of electrons, protons, neutrons, etc. All of these works on quantum mechanics, which helps in Quantum Computing. Quantum Computer uses something called as "Fluid Quantum Reality".

Computers came all the way down from Classical Computers to Super-computers to Optical Computers to Molecular Computers to Atomic Computers to Quantum Computers. In the future, we will not need silicon chips, computers will be running on atoms not on silicon chips.

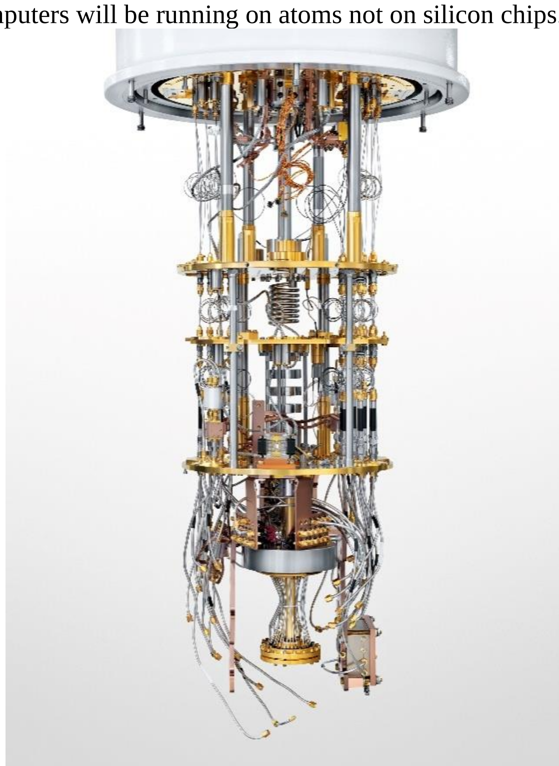

Fig. 7. Regular model of Quantum Computer

VII. CLASSICAL COMPUTER VS QUANTUM COMPUTER

The main difference between Classical and Quantum Computer is bit. Classical Computers run on Bits whereas Quantum Computers run on Qubits.

Classical Computers use linear computation for processing, so it's slow but could process few tasks for longer period of time.

Quantum Computers use parallel computation for processing, so it's fast and good at multitasking but could process multiple tasks for only a short period of time.

FUGAKU is the world's fastest Super-computer, while **IBM SUMMIT** is the world's 2nd fastest Super-computer till date. **SYCAMORE** is the world's fastest Quantum Computer developed by Google till date.

Since, 1950s to 2021, there had been massive development in the computation technologies. We evolved from Classical Computers to Quantum Computers but Quantum Computers can't replace Classical Computers or Super-computers as of now.

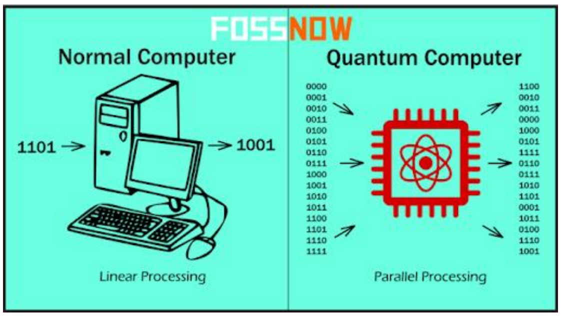

Fig. 8. Classical Computer vs Quantum Computer

VIII. QUANTUM INTERNET

Quantum Internet is sending quantum signals back and forth using photons through fibre optic cables. These photons represent **0** or **1**, and **0** and **1** at the same time due to Superposition and Entanglement. Quantum Internet is great for encryption because Quantum Entanglement is used for more security which makes the transfer of data faster than the speed light.

Quantum Internet will be securing quantum protocols, sending entangled information across campuses or cities, expanding the networks between states and across the whole country.

USA's Department of Energy (DoE) developed a blueprint of Quantum Internet.

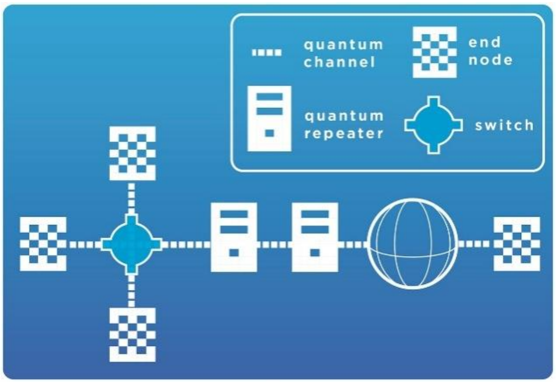

Fig. 9. Schematic diagram of Quantum Internet

IX. PHOTONIC QUANTUM COMPUTERS

In classical computers, data transfer and data computation are done with the help of electricity, where more processors are used for more processing power.

In case of Photonic Computing, data transfer and data computation are done with the help of light from the visible spectrum (**350nm – 700nm**), where parallel computing is used for more processing power.

A. Photonics: Why now?

Break through advances in photonic chip fabrication, optical telecommunication technology and architecture scaling is the reason why photonics is used.

B. Gaussian Boson Sampling (GBS)

A light source is sent through an integrated photonic chip, then it is detected by photonic number detectors and sent for further post processing. GBS could solve Dense Subgraph, Maximum Clique, Point Process, Graph Similarity, Vibronic Spectra, Quantum Enhanced Feature.

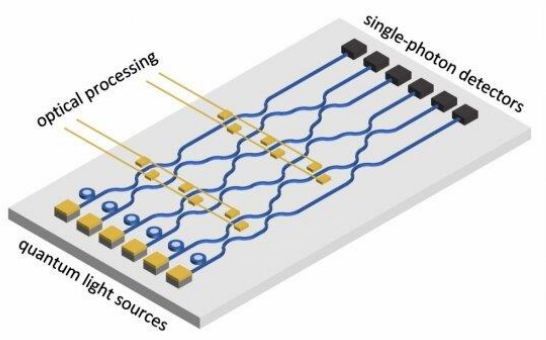

Fig. 10. Schematic diagram of GBS

C. Why Photonic Encoding?

Qubits from an input quantum state to an output quantum state are used to transfer data, since it follows quantum laws. Photons have some number of Degrees of Freedom (DoF), so they can be easily manipulated with high precision at about **99.9%** level. Since, photons have no charge at all, they are the fastest information carriers till date.

Optical RAMs are 10 times faster than SRAMs and 1000 times faster than DRAMs and uses **50%** less power consumption. Scientists can now switch between electrons and photons in a single transistor, so silicon photonics can transfer data at **1.2TB/s** up to 100m and **200GB/s** up to 50km. Fibre internet will use photonic wirings for Photonic Computing.

X. UNIVERSAL QUANTUM COMPUTER

Quantum Computers use quantum mechanics like Superposition and Entanglement, so all the Qubits are connected to each other. The time up to which information lasts in a Qubit is called "Coherence Time". Controlling the Qubits and the right architecture is the main difficulty in a Quantum Computer.

Companies like Rigetti, IBM, Google are investing in Quantum Chips, which are superconducting Qubits, basically silicon chips kept at a very low temperature, so that electrical and electronic resistance is zero.

Performance numbers are not good enough to build a fully functional and operational Photonic Quantum Computer, companies like Amazon, Microsoft, Rigetti, D-wave, Google, IBM, Xanadu are still working on it. Today Quantum Computers are where Classical Computers used to be at the beginning years back.

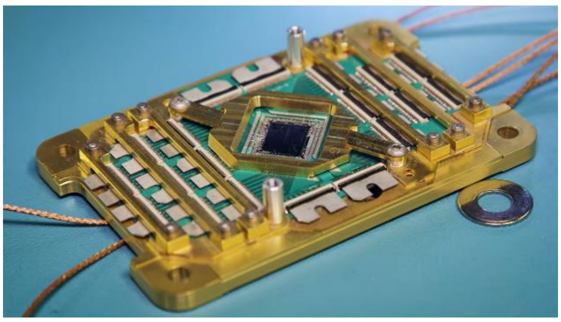

Fig. 11. Regular Quantum Processor

XI. APPLICATIONS

There are various applications of Photonic Quantum Computers like Weather Explorations, Traffic Monitoring, Space Communications, Manuscript Decrypting, Quantum Encryption, Drug Development, Teleportation of Information, Bioinformatics, Aerodynamics, Signal Processing, Financial Analysis, Medical Analysis, Defence, Oil and Energy, Banking, Chemistry, Logistics, Machine Learning, etc.

XII. ADVANTAGES AND DISADVANTAGES

A. Advantages

- Accessible, scalable, versatile and resource efficient.
- Modular and customisable.
- Well suited for distributed quantum computing.
- Friendly to environment.
- Unparallel robustness against noise.
- Highest possible clock rates.
- Arbitrary connectivity.
- No cryogenics and Vacuum systems.

B. Disadvantages

- Default photon sources are probabilistic.
- Entanglement operations are also probabilistic.
- Photon loss.
- Costly to develop.
- The materials are lossy.

XIII. CONCLUSION

Computers were from 1950s till date and since then there were many fixes, developments, innovations and technological advancements.

As technology grows, the need for more power and speed will undoubtedly grow along with it. The principal concern of Quantum Computer comes from the fact that it involves the use of Qubits. So, Photonic Quantum Computers are being developed as of now because it uses Photons.

Clearly the future of computing lies in Quantum Computing and it shows a lot of potential for future uses. With further research and experiments, Quantum Computers could be used everywhere. The world needs 1000s of connected Qubits to tackle useful problems. This is why there's so much interest, even though it's so far down the road, but for this to occur we have a long way to go.

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