Computation with Photonic Systems

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Things covered in this paper

- Why Photonic computing
- Photonic chips
- Realization of Logic gates
- Photonic peripherals
- Merging Quantum and Photonic computing

Why Photonic computing?

Today's computers rely entirely on electronic systems. Ever since the first computer was built, electronic transistors have been the heart of all computation. Now we have Quantum computing emerging as the next big thing, promising to break through many current limitations and forcing us to rethink how computers work.

Quantum computing uses materials called superconductors - special materials whose electrical conductivity changes with temperature. Other quantum approaches involve doing calculations using quantum states and complex mathematics, which we're getting closer to achieving.

Photonic computing takes a different approach entirely - it uses light and photons instead of electrons for computation. We already see photonic components in computing through optical fibers, those cables that transfer data faster than anything else, dramatically boosting data speeds. The same principle can apply to computation itself, where we replace every transistor and connection with light-based pathways or optical components on chips that carry information as light. The main things that slow down electronic computers are: Internal buffer systems, Thermal and resistive levels, High Power consumption and Signal noise and interference

Photonic computers don't mean completely ditching electronics - the light signals still need to be processed and the initial input has to come from electronic sources. So we still need electronic systems that can convert between light signals and electronic signals. Electronic instruments and photosensors become the key bridge components in these hybrid systems.

Some downsides of photonic computing I've identified:

- Converting between light and electronic signals requires additional components.
- Photonic systems still depend on electronic systems, so electronic limitations aren't completely eliminated.
- Photonic components need precise control of how much light they block/ let through
- Photonic systems naturally lack the ability to store information permanently

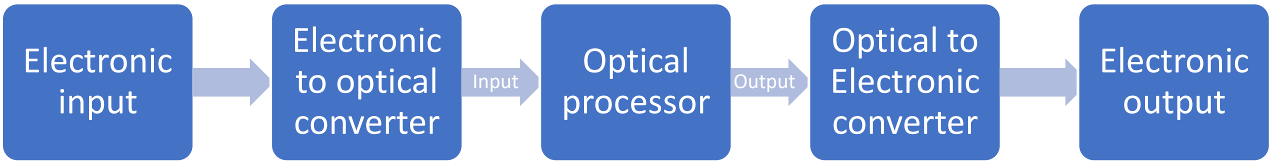


Figure 1: Block diagram of an optical system

Photonic chips

Digital chips contain billions of transistors and logic circuits, all connected and packed together at incredibly small nanometer scales. Replacing each of these systems with optical components that reflect and bend light (like lenses and mirrors) is extremely complex. The manufacturing process for photonic chips - including mask etching at VLSI levels - is similar to regular chips.

These chips don't need to be built at nanoscale though. Even a processor that's a meter wide with optical connections stretching for miles could outperform traditional systems by massive amounts.

Memory Systems: Why Flip-Flops Don't Work in Photonic Computing

In electronic computing, flip-flops are the fundamental building blocks of memory. A flip-flop is a bistable multivibrator circuit that can store one bit of information in two stable states - typically representing binary 0 and 1. These circuits rely on feedback loops where the output is fed back to the input, creating a stable state that persists even when the input changes.

How Electronic Flip-Flops Work:

Since photons travel at the speed of light and do not remain static, maintaining a state without continuous energy input becomes impractical. Electronic flip-flops use transistors arranged in specific configurations (like SR, D, JK, or T flip-flops) where the circuit can "remember" its previous state. The key principle is that electrons can be trapped in potential wells or capacitive structures, maintaining their state until actively changed by an input signal.

Why Photonic Systems Cannot Implement Traditional Flip-Flops:

1. Photons are constantly in motion at the speed of light. Unlike electrons that can be held in transistor junctions or capacitors, photons cannot be "stored" in a static state within optical materials.

2. Traditional flip-flops require stable feedback loops. In photonic systems, creating such feedback would require complex arrangements of mirrors and optical delays, but even then, the photons would eventually be absorbed or scattered, losing the stored information.

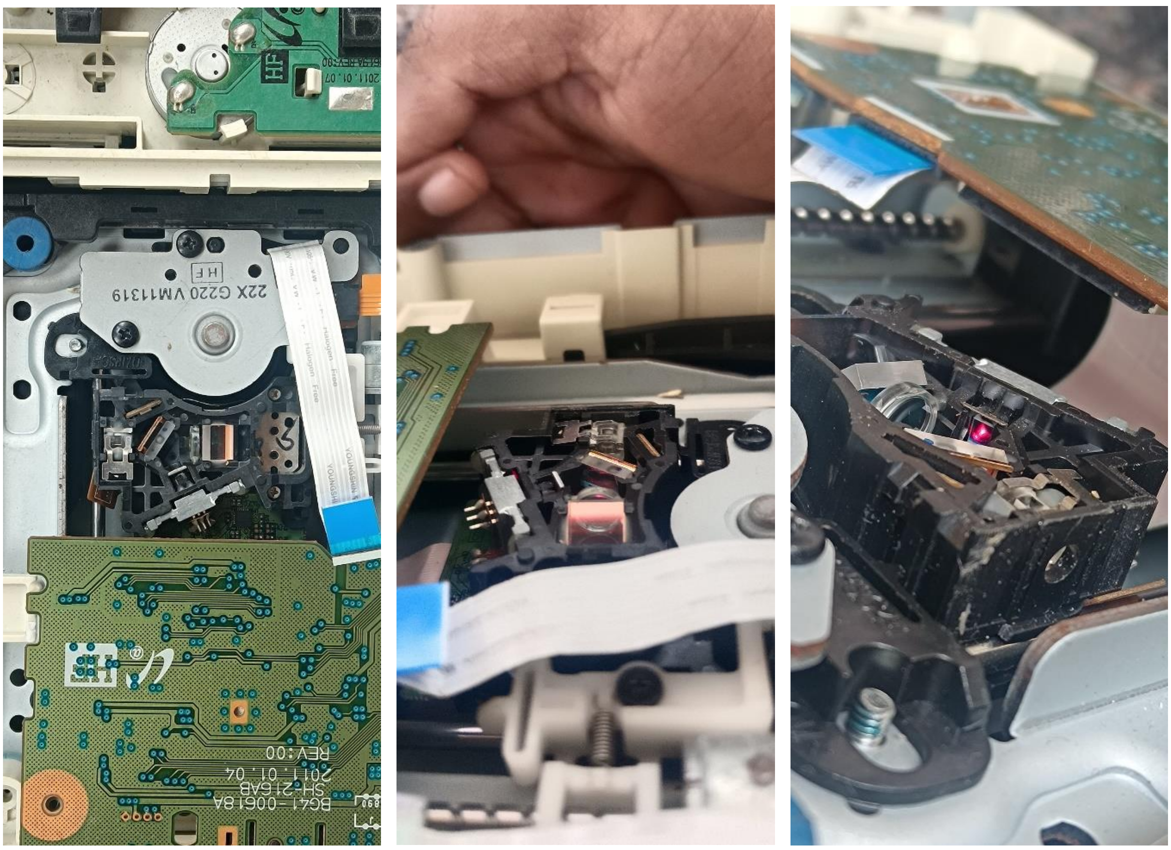
3. Light pulses are temporal events. Once a photon pulse passes through an optical component, the information is gone unless it's converted to another form (like electronic signals for storage).

Alternative Approaches in Photonic Computing:

- Optical Delay Lines: Using fiber optic loops to temporarily store information as circulating light pulses
- Hybrid Systems: Converting optical signals to electronic signals for memory operations, then back to optical for processing
- External Memory: Relying entirely on electronic memory systems while using photonics only for computation.

What I have done

I had an old optical DVD reader lying around in my room that I decided to get working again. The main component was a laser that focused on the spinning CD to read the binary data from laser reflections off the CD surface. The motor driver, laser controller, and the photo sensor that reads the reflections all convert to data signals.



(a) (b) (c)

Figure 2: (a) DVD reader teardown, (b) Side view of optical unit
(c) Optical module in operation

Figure 3.1: Back view of the optical module

Figure 3.2: Front view of the optical module

Inside the laser module was a set of lenses and sensors packed inside a metal block. Similarly, light signals can be controlled by properly aligning lenses and mirrors.

Realization of Logic gates

Photonic logic is the use of photons light in logic gates (NOT, AND, OR, NAND, NOR, XOR, XNOR). Switching is obtained using nonlinear optical effects when two or more signals are combined.

Resonators are especially useful in photonic logic, since they allow a build-up of energy from constructive interference, thus enhancing optical nonlinear effects.

Other approaches that have been investigated include photonic logic at a molecular level, using photoluminescent chemicals. In a demonstration, Witlicki et al. performed logical operations using molecules and SERS.

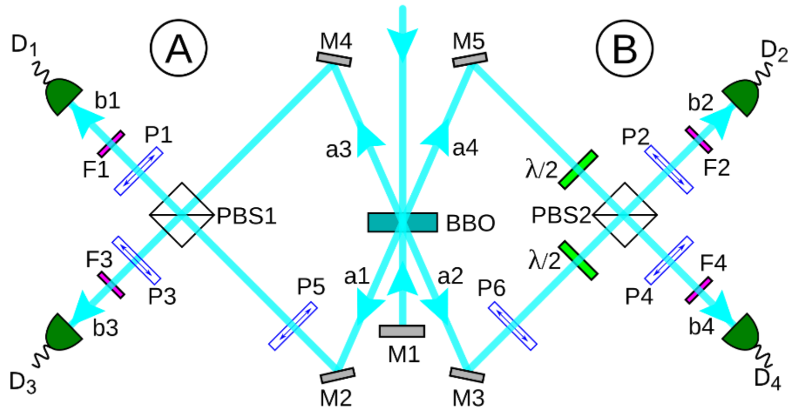


Figure 4 Realization of a photonic controlled-NOT gate for use in quantum computing

Here we have logic gates, with each pattern representing a different gate. When put together, these optical gates can form the building blocks of a photonic logic processor. The connections between these logic gates aren't metal wires but optical cable-like structures, eliminating the need to convert signals for each logic operation.

Training AI models requires enormous amounts of power, computation time, and processing. AI training with these systems could dramatically reduce power consumption and training time. AI modeling involves calculating data sets for each neural node among billions, based on linear and complex algebra. Since computation on optical chips is more efficient and faster, this creates huge advantages.

For AI applications, GPUs are in high demand - these are special processing units with parallel configurations instead of linear approaches. Photonic chips can also be built like GPUs, making them even faster.

In the early stages, instead of replacing entire systems with optics, some external devices or co-processors with optical components can push beyond current limits, even when integrated with conventional electronic systems.

So there can be many different versions of optical chips instead of just focusing on main processors.

Photonic Peripherals

Electronic chips and active components have bidirectional contacts and connectors, which are mostly metal-based. Metals aren't unidirectional conductors - they can conduct electricity in any direction. Electronic components with input/output pins have the ability to share data bidirectionally.

In optical systems, this property depends on the opaque materials used, and most are bidirectional. But the endpoint of an optical cable must have either a photo-receiver circuit or a photo-transmitter. The transmission between them always goes from a photo-transmitter to a photo-receiver, making it unidirectional. This presents a challenge, but there are potential solutions.

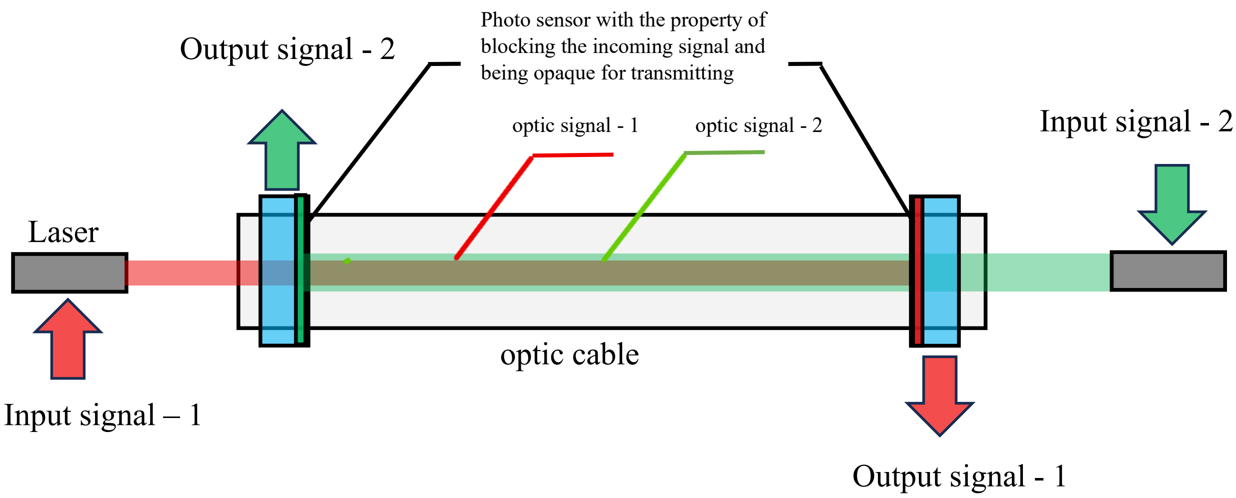


Figure 5: My concept of Bidirectional optic fibre

I spent the last 2 weeks designing a special type of optical cable that can solve this unidirectional problem. The diagram above shows how it works - it's pretty self-explanatory.

Merging Quantum and Photonic Computing

The convergence of quantum and photonic computing represents one of the most promising frontiers in computational technology. Both fields manipulate fundamental particles - photons in photonic computing and quantum states in quantum computing - making their integration both natural and powerful.

Why Merge Quantum and Photonic Systems?

Complementary Strengths:

- **Quantum Computing**: Excels at solving specific complex problems (cryptography, optimization, simulation) but struggles with scalability and error correction
- **Photonic Computing**: Offers speed, low power consumption, and natural parallelism but lacks the quantum advantage for certain computational problems

Shared Physical Medium: Photons are natural quantum objects that can exist in superposition states, making them ideal candidates for quantum information processing. This means photonic systems can inherently support quantum operations.

Conclusion

Photonic systems represent a promising frontier in the future of computation. While challenges such as memory storage and feedback circuits persist, the immense speed and parallelism of optical computation provide unmatched advantages. With advancements in integrated optics, these systems may eventually supplement or even replace traditional electronic systems in high-speed computing applications.