OPTICAL CPU PROTOTYPE

Part 1: Dual-Signal Optical Encoding, the Optical Transistor and Optical Logic Gates

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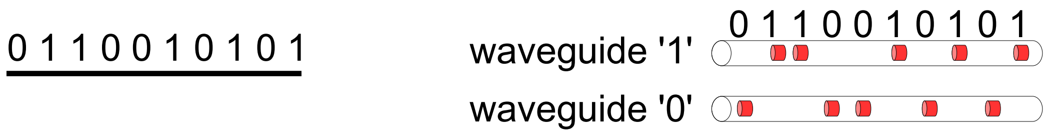
1 – Introduction

The viability, performance, and fabrication advantages of optical computing increase significantly when it is conceptualized as an all-optical system, especially when based on the very device that displaced electronics from communications: the laser.

To demonstrate this, the goal of this project is to build a basic all-optical CPU prototype. This requires three main components: an optical memory, optical logic gates and waveguides to connect them. This first part focuses on the development of the Dual-Signal Optical Logic Architecture (DSOLA), detailing the encoding method, the laser-based optical transistor and how these elements are combined to implement the fundamental logic gates: AND, NAND, OR, NOR, XOR, and XNOR.

2 – Dual-Signal Optical Encoding: Achieving Logic Without NOT Gates

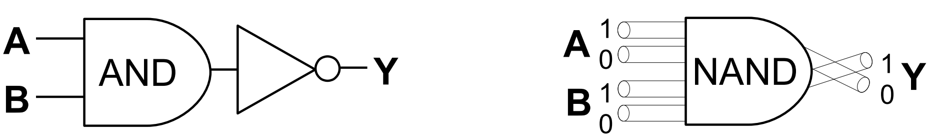
Unlike traditional binary electronic encoding, where a single wire carries a logic high (1) or low (0), DSOLA uses two separate optical waveguides: an optical signal in waveguide ‘1’ indicates logic high (1), while a signal in waveguide ‘0’ indicates logic low (0), ensuring that an optical signal is always present in the system, increasing data robustness in both transmission and processing.



Similarly, while an electronic logic gate typically uses three main wires (A, B, and Y), a dual-signal optical logic gate requires six waveguides to carry the dual-encoded inputs and outputs.

A	B	Y
1	1	1
1	0	0
0	1	0
0	0	0

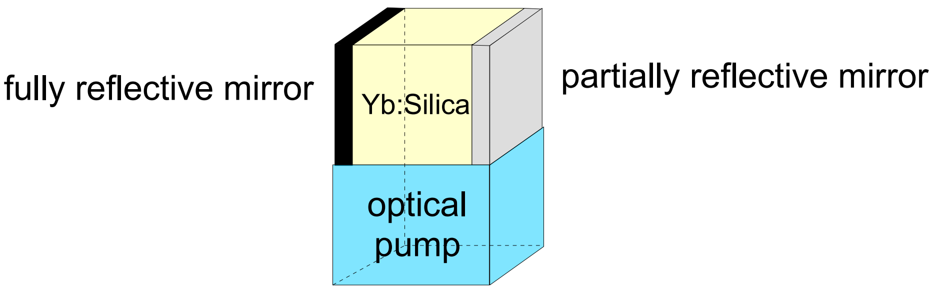
The first advantage of DSOLA lies in its simple logic reconfiguration. For example, reversing the output paths (Y) of the previous AND gate effectively transforms it into a NAND gate, without the need for additional NOT gates.



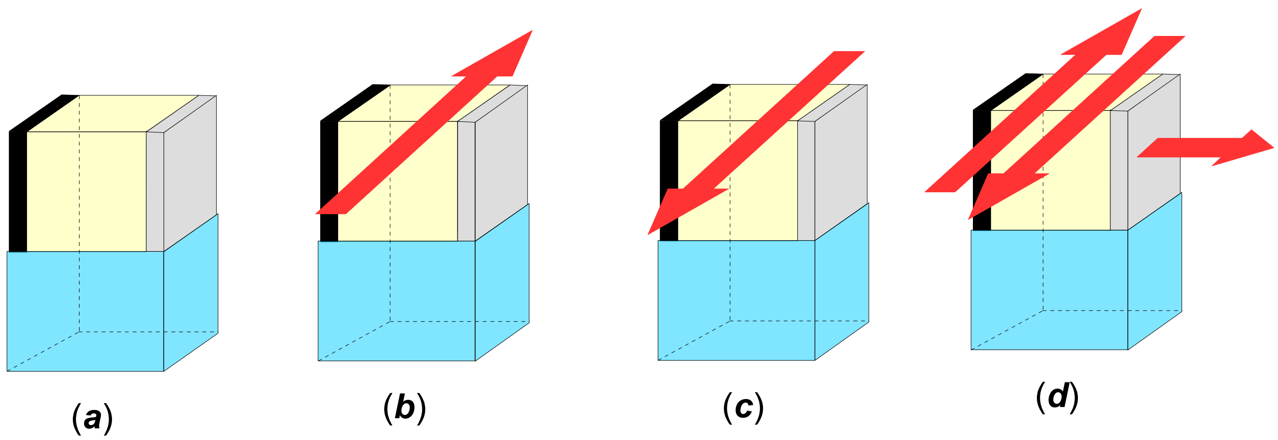
A	B	Y
1	1	0
1	0	1
0	1	1
0	0	1

3 – Laser-threshold transistor: A Building Block for Optical Logic Gates

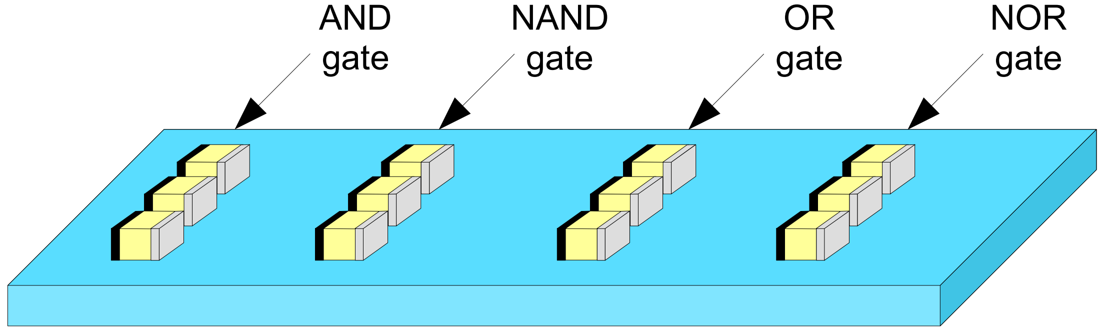
The laser-threshold transistor consists of a high-efficiency, optically pumped laser medium (e.g., Yb:Silica) positioned above an optical pumping source (e.g., diode laser). Fully and partially reflective mirrors form the optical cavity, directing the output laser beam in the desired direction.



The laser-threshold transistor operates as an optical switch, emitting an output laser beam only when two input laser beams are present simultaneously. The gain medium is optically pumped just below the lasing threshold (*a*). Each input laser beam alone lacks sufficient power to initiate lasing (*b*, *c*), but when combined, their total power exceeds the threshold, activating the Yb:Silica laser (*d*) producing an output beam through the partially reflective mirror.

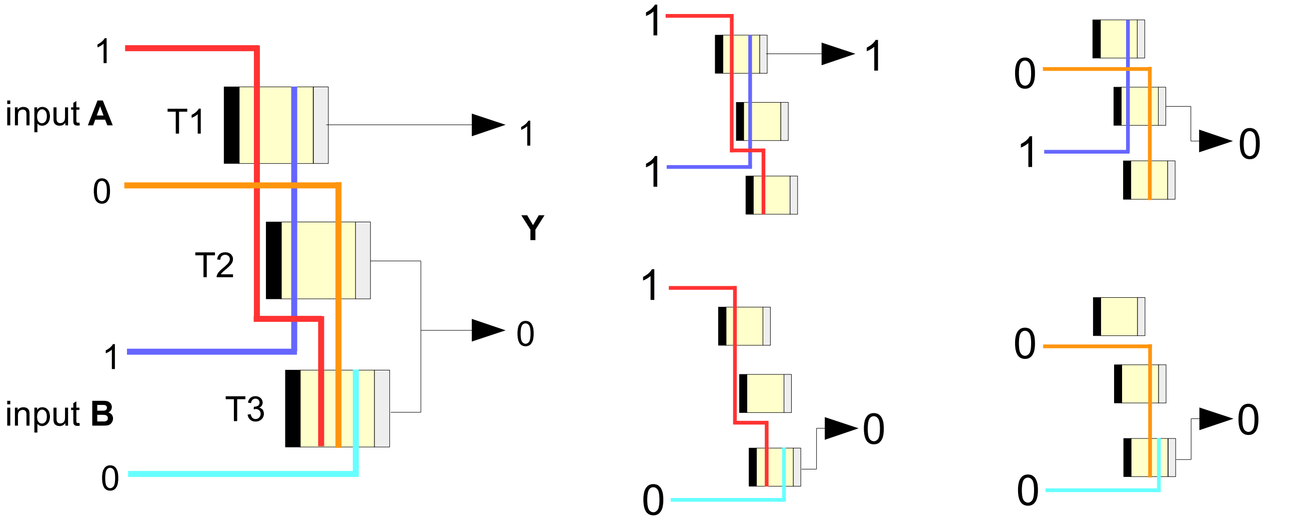


Another key advantage of DSOLA circuits is that they do not require individual optical pumps for each transistor. Instead, multiple laser-threshold transistors can be integrated on a shared, large-area laser surface, simplifying the overall fabrication for nanoscale integration.

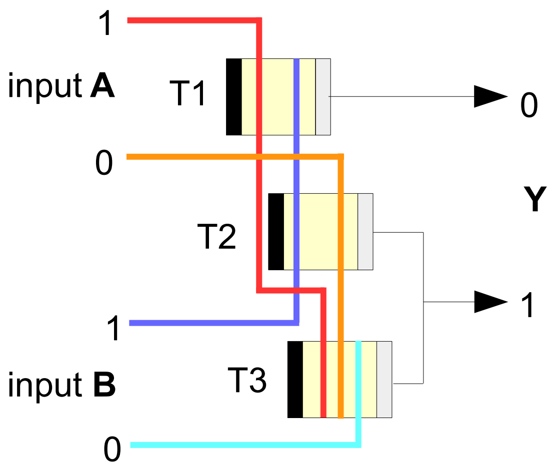


4 – Optical Logic Gates: Laser Speed Logic

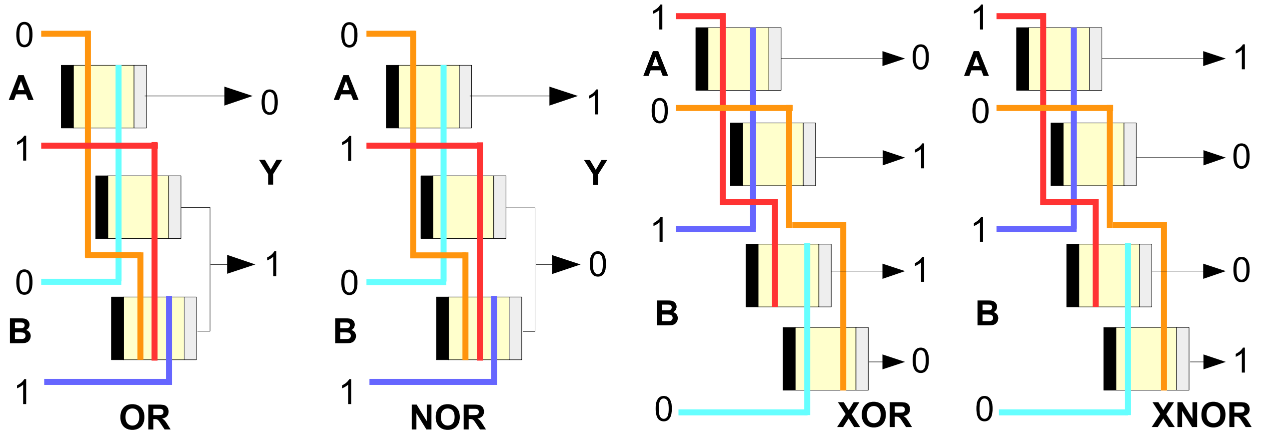
The AND gate comprises 3 laser-threshold transistors (T1, T2 and T3). T1 directs output to waveguide '1' for a logic high (1) result (Y). Both T2 and T3 direct outputs to waveguide '0' for a logic low (0) result (Y). The AND gate operates by selectively activating specific laser-threshold transistors based on the input combinations (A1, A0, B1, B0). A logic high (1) output is sent to waveguide '1' only when both inputs A and B are high (A1 and B1). For all other input combinations, the output is directed to waveguide '0' as logic low (0).



The NAND gate shares the same composition and function as the AND gate, with the key difference that T1 outputs to Y0, while T2 and T3 output to Y1.



The OR and NOR gates shares the same composition and function as the AND and NAND gates, with the different outputs. The XOR and XNOR logic gates have similar function with 4 laser-threshold transistors with specific outputs.



Another notable advantage of DSOLA circuits is that while most current laser applications require a strong output, the laser-threshold transistor operates with just enough energy to half activate the threshold of the next transistor. This significantly reduces the output power necessary lowering the energy consumption and heat generation, particularly at the nano-scale.

Moreover, for any input combination across all DSOLA logic gates (AND, NAND, OR, NOR, XOR, XNOR), only one laser-threshold transistor is activated per operation. This enables extremely fast logic execution with minimal delay and high syncronization in more complex circuits like coders, decoders, MUX, adders...

5 - All-Optical Fabrication: Beyond Silicon and Towards Simplicity

All-optical computing paradigms, such as the proposed Dual-Signal Optical Logic Architecture (DSOLA), offer fabrication advantages that are fundamentally unattainable with current electronic IC manufacturing. Although electrical power is required to operate the optical pump (e.g., a laser diode), the DSOLA circuits themselves are entirely optical, they require no electrical current to process or transmit data. As a result, there is no need for electrical contacts, charge carriers, or p-n junction materials. In effect, DSOLA eliminates the need for silicon entirely.

Instead of silicon, DSOLA circuits use Yb-doped silica (Yb:Silica) as the gain medium for optical transistors. Silica is already widely used in CMOS processes as a dielectric material, and it can be deposited using well-established techniques such as vapor deposition.

Silica also offers practical advantages over silicon: it is more abundant, less expensive, and easier to handle in uniform layers. Moreover, DSOLA circuits avoid the intricate multilayer doping and lithographic alignment required in silicon-based devices. They rely instead on homogeneous nanoscale blocks of optically active material, simplifying the fabrication process considerably.

6 - Conclusion

If experimentally validated, the Dual-Signal Optical Logic Architecture (DSOLA) offers a reliable method for dual-signal logic encoding. Its compact logic gates, driven by laser-threshold transistors, achieve ultra-fast operation with minimal energy, as only one laser activates per gate per cycle. A shared optical pump, powered by a single diode laser, simultaneously activates all transistors, simplifying circuit design and reducing power consumption. Furthermore, DSOLA’s fabrication leverages CMOS-compatible Yb:Silica deposition, which is less costly and complex than silicon-based processes, requiring fewer steps and no electrical interconnects. These advantages position DSOLA as a promising foundation for scalable, high-performance all-optical computing systems.