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From integrated photonic transceivers to all-optical logic

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ABSTRACT

Commercial telecommunications and internet data centers have made integrated photonic transceivers commodity products. We discuss the evolution of optical transceiver technology from direct detection to culmination in digital and analog coherent optic products for both fiber optic and free-space optical communication. Could this be a path for the convergent evolution of optical logic? We discuss the history of optical and electronic logic devices. We review recent work on coherent all-optical logic. We discuss new approaches using all-dielectric meta-surface structures in silicon photonics.

Keywords: All-optical Logic, Integrated Photonics, Coherent Optics.

1. INTRODUCTION

There is an ever-increasing world-wide demand for internet connectivity and bandwidth. This continues to fuel an evolution of commodity telecommunications components and systems. A key component is the optical transceiver (a.k.a. optical module or hot-pluggable) to convert digital electrical signals to optical signals or extend the communication distance of electrical signals. The optical transceivers serve a billion-dollar market. They provide a case study in high technology commodity item development. 850 nm wavelength 1 Gbps (1000Base) SFP transceivers sell for as low as $7 – even for single quantities. 1000Base-T is a shorthand designation by the Institute of Electrical and Electronics Engineers (IEEE). The 1,000 refers to the transmission speed of 1,000 Mbps, while "base" refers to baseband signaling, which means that only Ethernet signals are being carried on this medium. The level and quality of both electronic and photonic integration has increased over time as the transceiver data rates increase.

The market for silicon photonics is driven by the optical transceivers and is US$916.9 Million in the year 2020. It is projected[1] to reach a revised size of US$3.4 Billion by 2027, growing at a cumulative annual growth rate (CAGR) of 20.7% over the analysis period 2020-2027.

1.1 Direct detection transceivers

Commercial transceivers provide a cost advantage for both fiber optic and free-space optical communication. Although designed for terrestrial fiber optic links, the transceivers provide a compact, robust and Telcordia qualified design that is amenable for use in free-space communication links and navigation (laser ranging[2,3]) systems. The transceivers are characterized by their data rate and packaging. Wikipedia provides a comprehensive overview of the Small form-factor pluggable transceiver (SFP): https://en.wikipedia.org/wiki/Small_form-factor_pluggable_transceiver. 14 manufacturers created the Small Form-factor Pluggable (SFP) module with a Multi-Source Agreement (MSA) in 1999. In 2001, miniature Receiver and Transmitter Optical Assemblies (ROSA and TOSA) became available. In 2008, the SFP+ transceiver was introduced for 10 Gbps data rates. 850 nm wavelength vertical cavity semiconductor lasers (VCSELs) enable 400 Gbps data rates with 8 Non-Return-Zero (NRZ) intensity modulated channels operating at 53 Gbps.

For most free-space optical links an optical amplifier will be required for either or both the transmitter and receiver. This limits the available free-space transceivers to:

1) the telecommunications C-band (1530-1565 nm) for use with erbium-doped fiber amplifiers or

2) the 850 nm, 1310 nm (and possibly other near-IR) for use with semiconductor tapered flared amplifiers

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The increasing complexity of the level of photonic integration, digital signal processing and circuit (resistor, capacitor) parametric limitations and operating power makes it difficult to achieve the cost-competitive performance compared to moving to coherent transceivers[4].

1.2 Coherent detection transceivers

In 2007, the first 40 Gbps coherent transceivers[5, 6] were introduced that featured Application Specific Integrated Circuits (ASICs) with unique high-speed analog-to-digital converters (ADC) and digital signal processors (DSP). In commercial fiber telecommunications, coherent receivers with near-theoretical-limited receiver sensitivity are available when used in tandem with an erbium fiber preamplifier. The C form-factor pluggable (CFP) is the package standard from a multi-source agreement to produce a common form-factor for the transmission of high-speed digital signals. The c stands for the Latin letter C used to express the number 100 (centum), since the standard was primarily developed for 100 Gigabit Ethernet systems. The coherent transceivers in pluggable-form are available in Quad SFP Double Density (QSFP-DD) and CFP2 at 100 Gbps to 400 Gbps. The longest distance standard is the 100GBASE-ZR –module using standard LC dual fiber interface with single mode cable. Two phase-shifted - In-phase and Quadrature(I/Q) and two orthogonally polarized signals operate at 25.78 Gbps (times 4 gives 100Gbps) for up to 80 km distance fiber links. The coherent commercial transceivers are sold in two different formats: Digital Coherent Optics (DCO) and Analog Coherent Optics (ACO). The DCO transceivers include the digital signal processing (DSP) electronics in the package. In the ACO transceivers, the DSP is located off-module with the rest of the electronics and can support a lower data rate (i.e., 10 Gbps) than the typical 25 Gbps. Larger footprint non-standard package coherent optical transceiver modules are available[7, 8] that operate at > 1 Tbps.

The evolution of optical transceiver technology may provide key insights for the development of ultra-high speed all-optical logic. Are there lessons in the evolution of commercial optical transceivers for integrated photonics? Here are some possible lessons. 1) The development of integrated photonics is more evolutionary than revolutionary. 2) Electronics continues to evolve. Take advantage, rather than compete with the electronic evolution. 3) Smaller feature sizes in electronics enabled integrated photonic devices. 4) Silicon and indium phosphide design and manufacturing processes enabled integrated photonic devices. 5) The challenge is to find niches in application solutions where integrated photonics is complementary to electronic for a complete system. A starting point is with an integrated subsystem (example from telecom - transmitter or receiver) 6) Meeting the user demand for internet capacity with thousands of optical modules provides a commodity solution. It satisfies the customer needs, but only for a limited time. 7) The internet market demand and forces are moving to a fully integrated photonic solution that uses a coherent modulation format, the lowest possible power/energy, the highest possible operating frequency, and has a complementary role for electronics (digital signal processing). 8) The application (in this case - high-rate fiber communication) is driven by a solution that only optics can competitively provide.

2. ELECTRONIC AND OPTICAL LOGIC DEVICES

2.1 Digital-electronic logic limits

A universal computing-and-communication objective is ultra-low energy and high-speed switching. High speed electronic (transistor) switching is limited by the Power (P) dissipation product: $P \sim C*V^2$, V is the supply voltage and C is the capacitance. For reference, new Intel processors dissipate 165 Watts of power[9]. For this reason,[10], the CPU clock frequency stopped[11] increasing beyond 5 GHz in 2005.

2.2 Digital-optical logic

The use of optical interference (coherence) for digital logic originates in the adoption of radio frequency (RF) coherent communication techniques (i.e., optical discriminator) in the optical domain[12]. The optical discriminator evolved to the delay-line-interferometer and ultimately the optical-hybrid for today's multi-Tbps[13] (1.28 Tbaud) coherent digital receivers. The idea of digital logic using optical interference was introduced[14] in 1968 using free-space beamcouplers (a.k.a. beamsplitters). The beamcoupler method has evolved to present optical gate arrays[15,16] focusing on artificial intelligence[17] and neural networks[18]. Research on logic gates based on optical interference includes work with integrated photonic crystals[19, 20, 21], free space[22] devices, plasmon devices[23] and proof-of-concept experiments[24, 25] including a half adder[26] operating at 30 fs speed. Clader proposed[27] a microresonator based all optical transistor which evolved to a transistor[28] based on an atom coupling with a nanowire structure. For many of these ideas, device fabrication is extremely difficult.

The electronic logic operating frequency limited by circuit parasitic elements (resistance, capacitance and inductance). In contrast, optical logic can operate with master clocks at terahertz frequencies using mode-locked lasers[29] or frequency combs[30]. Electro-optic modulation speed is also limited by electronic parasitic elements. Lower clock-rate (10 GHz) streams are constructed with electro-optic modulators by gating femtosecond pulse streams (clock) for NRZ-to RZ conversion. All-optical approaches were developed for time division multiplexing[31] of lower rate streams to THz clock rate data streams. A 1.28 Tbit/s signal was obtained by 64-fold multiplexing of 10 Gbit/s signals. A key element is a nonlinear optical loop mirror[32] (NOLM) all-optical switch. A silicon photonics version of the NOLM was recently demonstrated[33].

3. IS THERE A ROLE FOR DIGITAL-OPTICAL LOGIC?

Digital-optical logic formats are in wide use in long distance communication links. As data rates increase the link distances decrease where optics can provide an advantage. The chip-to-chip electronic interconnects are the next target where high speed electronic serializer-deserializers (SerDes) input/output device power is significant. Chip-to-chip links[34] are characterized as Ultra Short (10 mm), Extra Short (50 mm), Very Short (150 mm), Medium (500 mm) and Long (1 m) reach. The SerDes line rate has steadily increased[35] from 1 Gbps in 1995 to 28 Gbps in 2020 with 56 Gbps in full development. Interconnects can consume up to 22% of the dynamic chip power[36]. Two challenges have been identified (Reference 36) (1) transistor density continues to increase, but the power used by each transistor no longer decreases at the same rate and (2) the power density of wires is increasing even faster than that of transistors due to poor wire size scaling. Data centers and their servers are estimated to account for up to 1.5% of global electricity usage. The internet data center per-rack power consumption is 20 kW. These few meter or less distance data links may provide a near-term opportunity for digital-optic logic.

4. LINEAR INTERFEROMETRIC OPTICAL LOGIC

Developing integrated-photonics cost-competitive low-energy hardware operating at higher data rates is challenging. In photonic circuits, logic functions can be realized by 1) linear interference effects and/or 2) non-linear optical processes. Since the energy-per-bit remains a major challenge, we focus on logic based on linear interference effects that we believe provide the lowest energy high-speed solution. For linear logic gates, the logic operation depends on the relative phase difference between two input signals, where the constructive or destructive interference of the input signals determines the corresponding logic operation.

We review recent experimental results. Birr et al. demonstrated (Reference 26) <30 femtosecond all-optical NOT, AND, OR, and XOR gate operations using linear interference effects and surface plasmon polaritons (SPP) in dielectric crossed waveguide structures. The interference takes place instantaneously and the switching effect in the waveguide junctions is intrinsically ultrafast. The device size is 10 μm x 20 μm. Further, they built a fully functional half-adder that integrated several cascaded SPP waveguide components and logic elements.

Shen et al. demonstrated[17] a prototype optical interference-based processor using integrated-photonic programmable Mach–Zehnder interferometers for a two-layer neural network trained for vowel recognition. They simulated the optical saturable absorber required processor nonlinear transfer function on a computer. They estimate that an optimized future device can operate at 100 GHz and use 100 times less energy per floating point operation (FLOP) than an electronic counterpart. Several start-up companies are working on similar technology 1) Lightmatter (https://lightmatter.co/) 2) Lightelligence (https://www.lightelligence.ai/) 3) iPRONICS (https://ipronics.com/) and 3) Luminous Computing (https://www.luminouscomputing.com/).
A field-programmable photonic array proof-of concept was demonstrated[37] using 30 Mach–Zehnder interferometers. Cao et al. demonstrated[38] a mesh-structure-enabled programmable multitask photonic signal processor on a silicon chip. The chip has 19 tunable MZIs, 20 electrode pads, and 20 input/output ports. They configured an optical interference unit (OIU)-enabled self-configurable router and switch. They characterized its operation using four kinds of different data information, 20 Gbit/s QPSK signal, 30 Gbit/s 8-ary quadrature amplitude modulation (8QAM) signal, 30 Gbit/s 8-ary phase-shift keying (8PSK) signal, and 40 Gbit/s 16-ary quadrature amplitude modulation (16QAM) signals. Miller[39] provides an algorithm and method for setting up optical meshes.

5. META-SURFACE DEVICES

Meta-surfaces are artificial materials with subwavelength features that act as miniature, anisotropic light scatterers. As a result, the phase, amplitude, and polarization of light can be engineered to provide the desired optical response. An application for optical interference meshes is the use of meta-surface devices as an alternative to DC-powered Mach-Zehnder phase shifters to directly engineer the required phase shift in the mesh structure. Many meta-surface integrated photonic waveguide device structures have been proposed and analyzed. Sun et al. recently provides an excellent review[40]. Yao et al simulated[41]. a proposed meta-surface integrated photonic waveguide all-optical logic gate[42]. The complete family of logic gates including NOT, AND, OR, XOR, NAND, NOR, and XNOR were simulated and analyzed. High contrast ratios of 33, 28, and 33 dB were predicted for the NAND, NOR, and XNOR logic gates, respectively, with the speed as high as 108 Gb/s.

6. SUMMARY

Commercial optical transceiver evolution may hold lessons for the continuing evolution of integrated photonics. Integrated digital electronic clock rates (5 GHz) stopped increasing in 2005. This provides a potential opportunity for higher clock rate all-optic circuits for high-speed digital-optical logic. Linear coherent (interference with phase modulation) processing may provide a low-power high-rate option for advanced digital logic. Beam splitter (a.k.a. coupler) and Mach-Zehnder meshes may find niche optical processing applications that are both competitive and complementary to electronic circuits. For meshes, clock rates, device size and power requirements are important. Meta-surface devices may provide an engineered phase-shift benefit in optical mesh networks. The ratio of simulation papers to experimental results is still very high. There is a need for more experiments and proof-of-concept devices. Meta-surface and subwavelength structures may be required for practical integrated photonic logic solutions.

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