Magnetically Controlled Switches for Optoelectronics Networking: The Problem, Available Technology, New Implementations

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This paper introduces some physical layer requirements of electro-optical as well as all optical networking. Due to the huge volume of data that is transmitted on these networks, there is a need for high-speed switching with effective switching in the nanosecond regime or better. While such switches exist for electronic media, they have been challenging for optical applications. Taking the recent developments in magneto-optical switches into consideration, there is a pressing need for fast switching of highly inductive loads. The state-of-the-art as well as the trends and needs for high speed switching in optical networks are presented. Some of the newest developments in the small-scale high-speed switching for electro-optical and all optical light path applications will also be presented. Experimental results of the newly developed switches at our program are presented and discussed. Based on the results, system requirements are identified and some shortcomings of the initial system are addressed. Possible improvements to the overall light-trail system are proposed and discussed.

Index Terms—**Faraday effect, magnetic switches, optical communication, optical switches.**

I. Introduction

OPTICAL communication dates back to antiquity; from fire and smoke signals to signaling lamps, flags and semaphores. Supplanted by electrical communications for a century beginning with telegraphy, optical communications made a comeback with the development of both a powerful coherent optical source that could be modulated (lasers [1]) and a suitable transmission medium (optical fibers [2]).

In the past four decades, during which light has been used as the signal of choice for long-haul data transport networks, many advances have been achieved; low-loss single-mode fibers, increasingly sophisticated modulators and longer carrier wavelengths among others. Taking the last decade in particular, the slower growth of voice traffic next to data traffic has led to a paradigm shift from connection-oriented communications to high-bandwidth IP-centric data traffic.

New applications in diverse areas such as home entertainment, corporate data storage, and avionics demonstrate an insatiable appetite for low-cost, reliable bandwidth. With new applications come new network protocols to better meet their requirements including optical burst switching [3], optical packet switching [4], multi-protocol label switching, and light-trails [5]. These all-optical architectures require a far different breed of network devices (e.g., switches, multiplexers, buffers) than those currently deployed in industry.

In this paper, we outline some physical layer requirements of emerging optical network architectures and the dissimilar nature and requirements of electrical and optical domain switching. A survey of state-of-the-art optical switch types is also presented with particular emphasis on those involving magnetic actuation. A detailed description of the performance of switches developed as part of the next generation optical network testbed at Iowa State University's High-Speed Systems Engineering (HSSE) laboratory follows. Finally, improvements and future research directions are discussed.

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II. Physical Layer Requirements

Wavelength division multiplexing (WDM) [6] was developed to enable networks to establish multiple point-to-point connections over a single fiber link by occupying multiple wavelengths, providing increased bandwidth and fault tolerance. A critical issue in current WDM implementations is their opaqueness due to reliance on optical-electronic-optical conversion at each intermediate network node. This requires nodes to be aware of the underlying packet format and bit rate. While this carries some advantages such as enabling grooming and monitoring, with current single-wavelength bandwidth on the order of tens of Gbps, the optical-electronic bandwidth mismatch is large and growing. Moreover, all legacy equipment has to be replaced in the event of an upgrade.

The protocols in the preamble address the electronic processing and switching inequities by moving the basic switching and routing network operations to the optical domain. These next generation WDM networks, whether coarse or dense require a fair amount of optical switches in cross-connects and add/drop multiplexers. Switches with different switch times for roughly three application classes are required; protection (ms), packet switching (ns) and bit-level optical time domain multiplexing (ps). They are analog in the sense that they do not make bit-by-bit decisions, routing the entire bit-stream oblivious to its contents. Thus, optical switches do not impose any additional throughput bandwidth limitations and inherently possess bit-rate and protocol transparency since end-to-end communication only depends on terminal equipment capabilities. It is the enabler of ever more reliable, scalable and richly connected optical networks.

III. Current Switch Technologies

Researchers are exploring different ways to replace the current electronic switch fabrics. Successful optical switching technologies should ideally demonstrate superiority in power consumption, scalability, insertion loss (IL), polarization-dependent loss (PDL), wavelength dependency, switching speed and crosstalk. It is the authors' opinion that the technologies discussed below have individual niche areas and it is highly likely that they co-exist on networks as each type represents different engineering tradeoffs.

The main contemporary switch technologies are micro-electromechnical systems (MEMS), acousto-optical (AO), electro-optical (EO), thermal-optical (TO) and magneto-optical (MO). MEMS switches are either free space (membranes, micro-mirrors) or based on planar moving waveguides. They also vary in the actuation mechanism used; electrostatic versus magnetostatic, latching versus non-latching. Free space variants suffer from higher ILs due to beam divergence ($\sim$3 dB), slower switching times (ms), high actuation voltage/current requirements and higher power dissipation for non-latching configurations ($\sim$80 mW). Waveguide variants offer faster switching times (100 ns) and lower ILs ($\sim$1 dB) at the cost of higher crosstalk (~ -30 dB).

AO switches are based on ultrasonic waves that deflect light. They offer good IL ($\sim$2 dB) and switch times ($\sim$40 μs) but have poor isolation (~ -20 dB) and wavelength dependency.

EO switches are among the most mature available; SOA, $LiNbO_3$, liquid crystal, electroholography and switchable waveguide Bragg gratings. Depending on the variant, they offer ILs ranging from <1 dB to 10 dB, switch times from 10 ns to 1 ms and isolations of -10 dB to -40 dB. However the majority of them have a strong wavelength dependency and those that do not are typically subject to higher ILs. SOA-based switches also suffer from a limited dynamic range.

TO switches are based on either the thermal behavior of materials or the waveguide thermo-optic effect. While having excellent PDL, they consume more power due to the heating process ($\sim$70 mW) and have a slow switch time ($\sim$10 ms).

MO switches are based on the Faraday rotation of polarized light when it passes through a MO material in the direction of an applied field. Recent advances in bismuth substituted iron garnets (BIGs) [7] and orthoferrites [8] has yielded materials with a high MO figure of merit, giving low ILs, ultrawide bandwidths and a higher degree of rotation for less applied field. Didosyan *et al.* [9] demonstrated a latching, free space switch using $YFeO_3$ that shows promising results (sub-100 ns switch time, low power dissipation) despite the high insertion loss and additional hassles (beam collimation, alignment, etc.) due to its free space nature.

Switches utilizing magnetic actuation including MO and free space MEMS switches warrant a specific set of engineering considerations. High field intensities on the order of 20 kA/m are typically required. Heating may be utilized for thermomagnetic switching [10]. For non-latching switches, the power consumption to maintain the switch state needs to be minimized. Hysteresis of the domain wall motion is also a potential issue as this translates directly into hysteresis in Faraday rotation, which is detrimental in Mach-Zehnder interferometric configurations. The high switching currents engender reliability concerns due to electromigration. Lastly, the size of individual switches and switch fabrics is dictated by the size of the field-generating elements and shielding requirements to minimize crosstalk.

IV. Implementation and Results

A 1.3 μm wavelength light-trail test bed was implemented to further the exploration of all-optical network design. The testbed utilizes a Xilinx VirtexII Pro FPGA development board and Ignis Optics IGE-2000 SFP Fabry-Perot laser module for each node. The serial data stream to the lasers is derived from RocketIO Multi-Gigabit Transceivers [11].

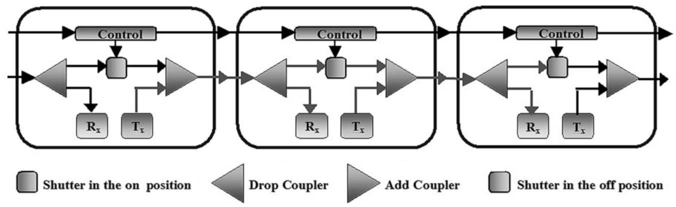

Fig. 1. A three node light-trail showing the primary LAU components.

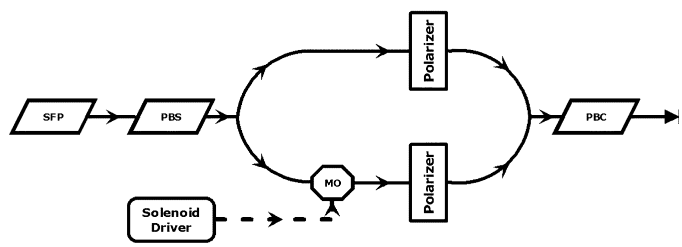

Fig. 2. Implementation overview of the MO switch with a single FR.

Light-trail is a physical layer architecture designed to handle IP-centric traffic patterns more effectively than optical circuit, packet or burst switching. Applied to WDM networks, its design goals are to maximize wavelength utilization and minimize active switching while supporting multi-granularity traffic by combining commercially available components with emerging network technologies to provide a transparent, reliable and highly scalable communications network.

A light-trail (see Fig. 1) is analogous to a light-path in that it involves the establishment of an optical circuit between a chosen source and destination. However, intermediate nodes can receive and transmit data on a common channel on separate wavelengths. Each node [a light-trail access unit (LAU)] consists of a splitter, shutter, combiner and power compensator. The signal traverses all nodes en route. Each node taps a sufficient amount of optical power for processing and shutters the remaining signal. The non-shuttered signal is added to the local transmitter signal during channel access.

A high-bandwidth optical switch is required to act as the shuttering element at each LAU. To this end, an all-fiber MO switch is proposed and developed to address the shortcomings of other optical switches. The state of polarization (SOP) is dependent on the direction and magnitude of the applied field and this is used to turn the optical signal on and off.

The proposed switch uses a latching BIG as the Faraday rotator (FR). As shown in Fig. 2, it consists of a polarization beam splitter (PBS), a single FR, polarizers and a polarization beam coupler (PBC) [12]. The PBS splits the input signal from the common fiber channel into two orthogonal linear polarizations. When the SOP is rotated 90° away from the optical axis of the polarizers by applying an external field, the optical signal is blocked and the switch achieves an OFF state. The SOP remains unaltered in the ON state. The PBC adds the processed signals and feeds it back into the common channel.

The manufacturer specified rotation of the FR is 45° at a saturation field of 27.9 kA/m. This applies to the standard case

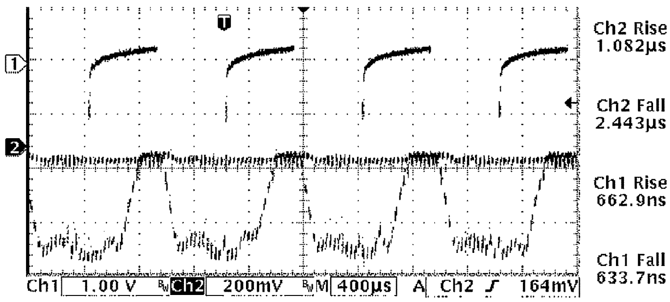

Fig. 3. Solenoid voltage (Ch 1) and transimpedance amplifier output (Ch 2).

where the light beam diameter should encompass a random, large number of up and down domains to average out the effects of local domain orientations. In the current testbed, multimode fibers with a 65 μm core diameter were utilized. Thus, the beam only looks at 2–3 FR domains and this exhibits different behavior than the typical case described. A domain that is anti-parallel to the applied field provides approximately 45° of initial rotation and another 45° once fully saturated. Consequently, 90° of rotation was obtainable at a field of only 12.7 kA/m leading to significant design simplifications. The forward and reverse latching fields are generated by biasing a multi-layer solenoid with appropriate 5 A currents.

For functionality tests, the use of a simple ON–OFF switch is sufficient. In a practical implementation however, the optical switch needs to be controlled from the Xilinx FPGA of the test bed. Due to its criticality in network reconfiguration, the MO switch response time needs to be minimized. This necessitated the design of a solid-state solution that provides sharp current rise/fall times while being able to drive the large 1.3 mH load presented by the solenoid. The designed solenoid driver utilizes four MC33886 H-bridges in parallel to provide a maximum bi-directional current drive of 20A that can be pulsewidth modulated up to 10 kHz.

The overall switch was measured to have a 4.5 dB IL, 19 dB extinction ratio and 2 μs switching time (see Fig. 3), which the authors consider promising for a proof-of-concept prototype.

V. Improvements and Future Directions

The MO switch is still operating at speeds well below what is achievable. In principle, the speed of the polarization plane rotation depends on the velocity of the domain walls. This has been measured to be on the order of 10 kms^{-1} [13], resulting in a switching time of 100 ns [9]. However, the time constant associated with the field-generating coil currently overshadows the delay associated with the FR domain dynamics. The stability of the extinction ratio is also a source of concern due to the irreversible displacement of domain walls caused by energy minimization in defect sites. One possible approach to stabilize the magnetic domains is to etch the thin film into separated islands [14]. The IL can be improved by the use of a refractive index matching liquid with low viscosity, low volatility, and high thermal stability [15].

Detailed modeling and measurement of the coil impedance parameters are being performed in the process of investigating improved driver and coil configurations. The aim is to minimize the required current, back emf and inductance. Classical techniques such as the use of keepers [16] to reduce EMI and thermomagnetic switching [10] to reduce the required field are also being examined.

Additionally, different switch topologies are being evaluated (e.g., the Mach–Zehnder interferometric configuration presented in an accompanying paper [17]). The current MO switch is also being migrated to 1.55 μm, where a thicker film is required, leading to possibly different domain wall dynamics. Lastly, a photonic integrated circuit version of the switch using a silicon substrate is being explored.

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